PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

DYNAMIC SIMULATIONS FOR THERMAL AND LIGHTING BEHAVIOR OF OFFICE BUILDINGS IN SANTIAGO OF CHILE

ALAN M. PINO ARAYA

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering.

Advisors:
WALDO BUSTAMANTE GÓMEZ
RODRIGO ESCOBAR MORAGAS

Santiago de Chile, August 2011

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To Loreto, my beloved little sister.

Don't ever be afraid to aim higher.

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CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

ABSTRACT

Overheating, high cooling energy load and glare are recurrent problems in office buildings in Santiago, Chile. In this country there are no legal regulations about thermal performance in this type of buildings. Moreover, the available information about their thermal behavior corresponding to different Chilean climates is limited. The climate of Santiago is a temperate climate with winter rains and a 7 to 8 month long dry season. It shows a high temperature oscillation between day and night (around 14 ºC) during the summer season.

In order to achieve energy efficiency, it is necessary to know the influence of different architectural strategies in the thermal comfort of the users and/or the energy load to heat or to cool an office. Then, with complete and appropriate information about the thermal performance of office buildings, it will be possible to standardize their building design. In this study, based on computer dynamic simulations, cooling and heating energy loads are estimated for an office building located in Santiago, which has been specially designed for this purpose. Variations on the glazed area, type of glazing, types of solar protection and orientation were assumed in order to evaluate their influence on building energy loads. It has been shown that the size of envelope`s glazed areas highly influences the energy loads. A totally glazed façade building might reach up to 155 kWh/m^2·year for total cooling and heating loads. On the other hand, a building with lower windows area (20% of window-to-wall ratio), external solar protection and selective glazing might load as low as 25 kWh/m^2·year. If night ventilation is applied during cooling periods an additional reduction of 37% of the total energy loads can be achieved. A 20% of window-to-wall ratio is enough to avoid glare and to keep a Useful Daylight Illuminance (UDI) around 80% of the working hours throughout the year. The main conclusions of this work are: i) for the climate conditions of Santiago, completely glazed façades, are not recommended, even with selective glazing; ii) night ventilation shows to be highly effective to reduce cooling loads; and iii) lower window-to-wall ratios (20%), with solar protection can achieve a better daylight performance than larger ones due to prevention of glare.

Keywords: Office Buildings, Heating Demand, Cooling Demand, Thermal Comfort, Visual Comfort.

RESUMEN

Sobrecalentamiento, altas cargas de refrigeración y deslumbramiento son problemas recurrentes en los edificios de oficinas de Santiago de Chile. Actualmente, en el país no existen regulaciones legales sobre la eficiencia térmica de este tipo de construcciones. Adicionalmente, la información disponible sobre el comportamiento térmico de éstos para los diferentes climas que existen en Chile es limitada. El clima de Santiago tiene estaciones muy marcadas y presenta una gran oscilación de temperatura ambiental entre el día y la noche durante el verano (alrededor de 14ºC).

Para poder lograr una eficiencia energética es necesario saber la influencia en el confort de los ocupantes, o bien, en la carga de energía para refrigeración y calefacción que tienen distintas estrategias arquitectónicas utilizadas actualmente. Luego, al contar con información completa y apropiada sobre el comportamiento térmico de los edificios de oficina para un clima en específico, será posible normar acerca del diseño de estos edificios.

En esta investigación se estiman, por medio de simulación computacional, las cargas para refrigeración y calefacción que tiene un edificio tipo ubicado en Santiago especialmente diseñado para este propósito. Se han considerado variaciones en la razón entre áreas vidriadas y el total de la envolvente, el tipo de vidriado y de protección solar utilizado y la orientación de las oficinas para evaluar la influencia que tienen estas variables en las cargas de energía del edificio.

A partir de los resultados se muestra que la porción de la envolvente vidriada es la variable que más influye en las cargas de energía. El edificio estudiado puede llegar a requerir 155 $kWh/m^2 \cdot$año para alcanzar un estado de confort térmico, si su envolvente está completamente vidriada. Por otro lado, si este edificio tiene ventanas más pequeña, utiliza elementos de protección solar y tiene vidrio selectivo, las cargas totales puede bajar a 25 $kWh/m^2 \cdot$año. Adicionalmente, si se aplica ventilación nocturna durante los periodos de refrigeración se puede lograr una reducción adicional del 37% en las cargas totales. Un 20% de la envolvente vidriado es suficiente para mantener una iluminación natural adecuada durante el 80% del total de horas de trabajo al año. Las principales conclusiones son: i) para el clima de Santiago no es recomendable utilizar envolvente completamente vidriadas, ii) la ventilación nocturna se muestra como efectiva para reducir las cargas de refrigeración, y iii) se logra una mejor iluminación natural con ventanas pequeñas y protección solar, que con ventanas más grandes.

Palabras Claves: Edificios de Oficinas, Demanda de Calefacción, Demanda de Refrigeración, Confort Térmico, Confort Lumínico.

1. INTRODUCTION

1.1 Motivation

World population has grown steadily since the Industrial Revolution, mainly through agricultural improvement and the development of new advances in medicine and hygiene. The U.S. Census Bureau reveals that the world's population currently exceeds 6,800 million people. Although the growth rate is expected to decrease, the world's population could still reach 9 billion people by 2050 (U.S. Census Bureau, 2010).

Chile follows this world trend of population increase. Furthermore, the majority of the country's rural population has shifted to urban areas, increasing population density in major cities. This phenomenon produces problems such as energy-intensive consumption, traffic congestion, pollution, complexity in the management of garbage and sewage, and more. The Metropolitan Region's total population (urban and rural) doubled between 1960 and 1992. By 2002 the population had already surpassed 6,000,000 people, nearly 97% of them living in urban areas, as can be observed in Figure 1-1 (Instituto Nacional de Estadísticas (INE), 2008).

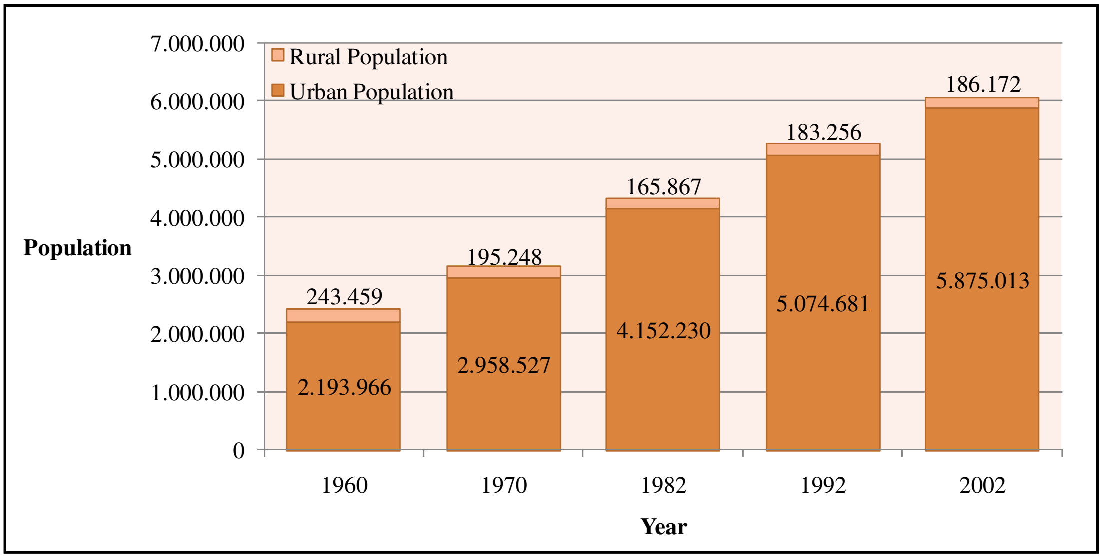

Figure 1-1. Population evolution of Metropolitan Region. (Instituto Nacional de Estadísticas (INE), 2008)

Considering the sustained population growth in a finite planet- where food, energy resources and raw materials are also finite – it is necessary that we improve the efficiency of the use of these resources.

It is key to recognize the difference between saving and efficiency. Savings aims to bring down the cost of an activity in units of time, money or energy, primarily by reducing or avoiding such activity. Energy efficiency, aims to do the same amount of activity at a lower cost or to do more activities at the same cost, in units of time, money or energy. It is worthy to note that energy efficiency leads to savings but not necessarily vice versa.

The 4th Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) has confirmed that a global warming process is underway. This process is directly related with greenhouse gases (GHG), generated mainly by human activity. The atmospheric concentration of GHG, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (NO_x) has increased by 70% between 1970 and 2004, primarily due to the use of fossil fuels (IPCC, 2007).

Considering environmental and energy issues, it is a priority to increase energy efficiency while seeking alternatives to fossil fuels. This involves the whole energy transformation process; from the extraction of the resources until end use of energy as products or services. Therefore, a study has emerged on finding ways to increase energy efficiency in office buildings without compromising user comfort.

1.2 Energy in Chile and the World

Today, the world faces serious environmental problems and low availability of energy resources. Much of the world's primary energy comes from fossil fuels, principally oil, natural gas and coal. These resources are not renewable, so its exhaustion is a future reality.

The comparative advantage of fossil fuels is that they have high energy density per unit of mass making them the preferred energy sources for transportation. Intermittent generation due to resource availability profile of renewable energy (solar, wind, waves, tides, etc.) produces an entry barrier in addition to the high cost of these technologies. Nuclear energy has significant potential to mitigate climate change because it does not emit greenhouse gases. And has a high capacity factor— a modern nuclear reactor can achieve its goals close to 90-95%. However, the nuclear fuel resource is finite and there is high social apprehension about nuclear power due to its war development and accidents in Chernobyl (USSR), Three Mile Island (US) and most recently in March 2011, Fukushima (Japan).

Within the last 40 years, the world's primary energy consumption has doubled, although there has been a slight percentage decrease in the use of fossil fuels as primary sources from 86% in 1971 and 81% in 2008, as shown in Figure 1-2 (International Energy Agency, 2010).

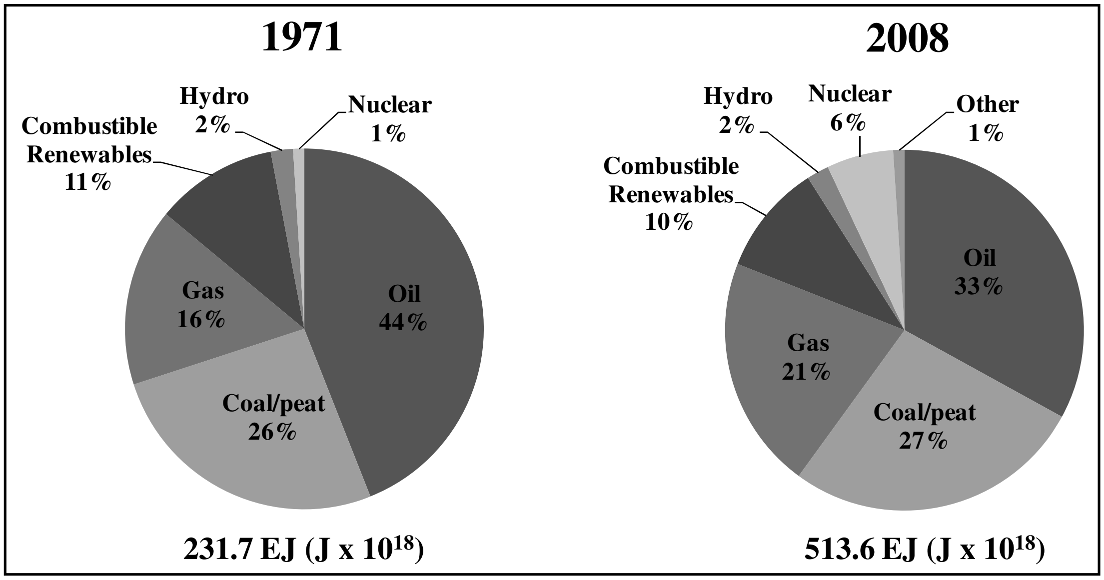

Figure 1-2. World's Total Energy Supply by fuel. (International Energy Agency, 2010)

Chile, like the rest of the globe, uses a high percentage of fossil fuels. The presence of these fuels in the Chilean primary energy matrix is over 70%. Moreover, because Chile imports almost 90% of its fossil primary energy, it is significantly energy dependent (Comisión Nacional de Energía (CNE), 2008). This affects the stability of the energy matrix by the variability of market prices and supply reduction or outages. The price of some fossil fuels is affected by political situations of the major exporting countries as seen in the rise of oil prices due to war in the Middle East. From the increase in oil prices, there is a rise in the price of other products as fossil fuels are most commonly used in transport segment and power. Also, we can mention the energy crisis that Chile suffered because of natural gas from Argentina, whose supply fell from 2004 to reach an outage in May of 2009 (AGNCHILE, n.d.). Moreover, the environmental consequences related to the use of fossil fuels, both local and global, must be considered.

The interconnected power system that provides electricity to the Metropolitan area (SIC) is the largest in the country and by 2009 52% of its installed capacity was from thermoelectric plants (Comisión Nacional de Energía (CNE), 2009). The second largest interconnected power system (SING) provides electricity to northern Chile; 99.6% of its installed capacity was from thermoelectric by 2009. At the southern end there are two more interconnected power systems, Aysén and Magallanes, which also have a high percentage of fossil fuels in its electric matrix. Figure 1-3 shows installed capacities and geographical area covered by each of the 4 interconnected power systems of Chile.

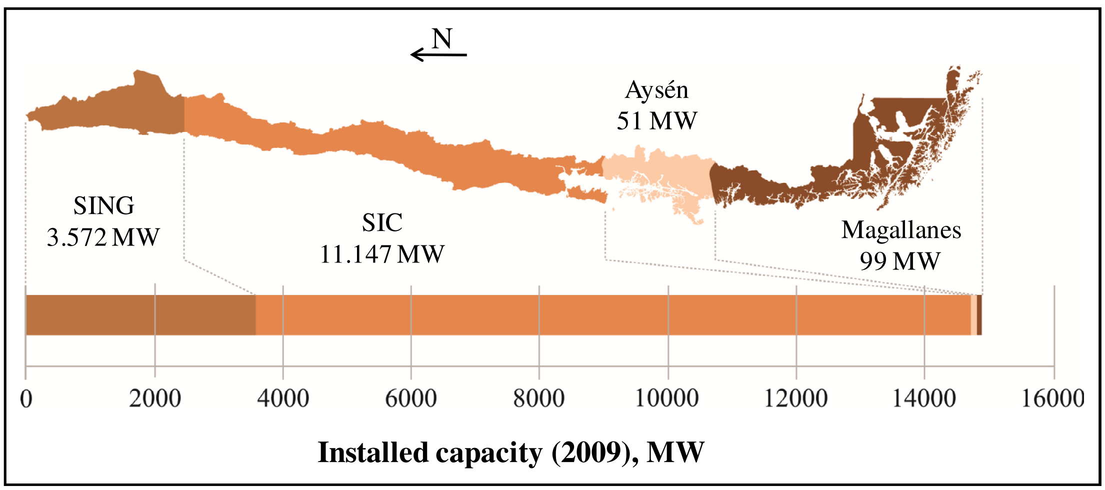

Figure 1-3. Installed capacity of interconnected power systems of Chile.

During 2008, national electricity consumption for Public and Trade sectors, which includes office buildings, was 7,340 GWh. This amount was slightly lower than residential consumption (8,750 GWh) in this year (Comisión Nacional de Energía (CNE), 2008).

1.3 Energy in Buildings and Heat Transfer

The main mechanisms of heat transfer are conduction, convection and radiation. Inside of a building, the movement of air masses must be considered, which through advection transports heat and/or moisture between sections and the outside. All or combinations of these transport mechanisms may occur into, out of and around the building. Moreover, as the temperature inside and outside a building varies depending on time of day and season of the year, it is necessary to calculate the heat flows in a dynamic state.

Conduction is a heat transfer mechanism in which the flow occurs by direct contact between the particles of one or more bodies in contact. The amount of heat transferred is determined by the Fourier Law and is directly related to the temperature of the bodies' ends and their thermal conductivity. Its use in buildings is mainly based on the calculation of heat flow through walls, windows, doors, ceiling and floor. Usually construction elements in buildings have different layers of different materials.

The heat transferred by means of fluids (e.g. water or air) is known as convection. The Newton's law of cooling expresses that the convective heat flux depends on the convection coefficient, the surface and the temperature difference between the body and a distant point within the fluid. The convection on the building envelope is calculated by using a series of theoretical and empirical correlations relating to the heat flux with temperature difference, the orientation of the surface and for the outer case, with the wind speed and direction. It can occur naturally or by forced convection. The first is related to differences in densities of a fluid due to a temperature gradient, where generally, the higher the temperature of the fluid, the less dense it is and it will create an upward movement of the molecules that are warmer. Moreover, forced convection is related to the motion produced by a fan, pump or other mechanical device on a fluid that comes in contact with a body, which delivers or extracts the heat.

Electromagnetic radiation is a heat transfer mechanism were particles of energy or waves travel through a medium or space. Any substance which has a temperature above absolute zero emits thermal radiation. The radiation heat transfer is expressed through the Stefan Boltzmann law and is directly related to the emissivity of the body and the fourth power of its temperature. In buildings, is important to study the radiation for two main reasons. The first is that glass (i.e. windows) is transparent for frequency waves in the visible spectrum (light) but is opaque for short waves (heat). This causes that energy to enter as light through windows and heats the interior surfaces but this heat cannot leave the space as radiation through windows, which generates heat gains. The second reason is the sensation of people from radiation with surrounding bodies. Although the air temperature is comfortable when the temperature of the walls that surround a person is low, it is possible that this person does not feel comfortable because of his/her loss of heat by radiation.

The elements that generate heat inside the building can be considered as internal or external gains. The internal gains are mainly heat generated by lighting, equipment and occupants. This heat is modeled mainly as convection with the indoor air and radiation to other bodies and indoor surfaces. The heat of occupants can be separated between sensible heat by the action of a temperature gradient, and latent heat by the action of a phase change (e.g. breathing and perspiration). Usually, office equipments do not provide latent heat like other electric devices (water boilers), so the heat input from light and small equipment for this study are considered just as sensible heat.

On the other hand, the main external gain is solar and might be an important agent in the energy balance of a building if there are not strategies considered to control solar radiation. Solar radiation entering a zone through transparent building components falls on internal surfaces, where it may be absorbed, reflected or transmitted depending on the surfaces' properties. Distribution of absorbed and transmitted solar radiation can be accounted as heat.

Air exchange with the exterior of the building occurs through ventilation and infiltration. Ventilation can be natural, e.g. opening a window; or mechanical, by fans and extractors. In this study mechanical ventilation able to get outdoor air requirement standards, i.e. the minimum recommended air changes to reduce concentrations of contaminants or unwanted gases inside an office, was applied. Besides, infiltrations are unintentional exchange of outside air into the building. They occur mainly through gaps in the building envelope or through doors due to the movement of people. The amount of air exchange can be estimated by empirical methods. You can decrease the value of infiltrations by improving the quality of unions - mainly windows, doors and ceiling - or by increasing the pressure inside the building using mechanical systems. However, the infiltration cannot be controlled by users and are generally considered undesirable due to the entry of dust, reduction of thermal comfort and increase of energy consumption.

Figure 1-4 shows the main mechanisms of energy transfer within a building. Energy transfer can be observed as internal gains by lighting, equipment and people, as well as direct solar gain and the reflection in the sky and ground. It also shows the heat interchange by conduction, convection and radiation through the building envelope. Finally, we illustrate the thermal conditioning equipment and their respective heat transfer mechanism, specifically an air conditioning (cooling) and a radiator (heating).

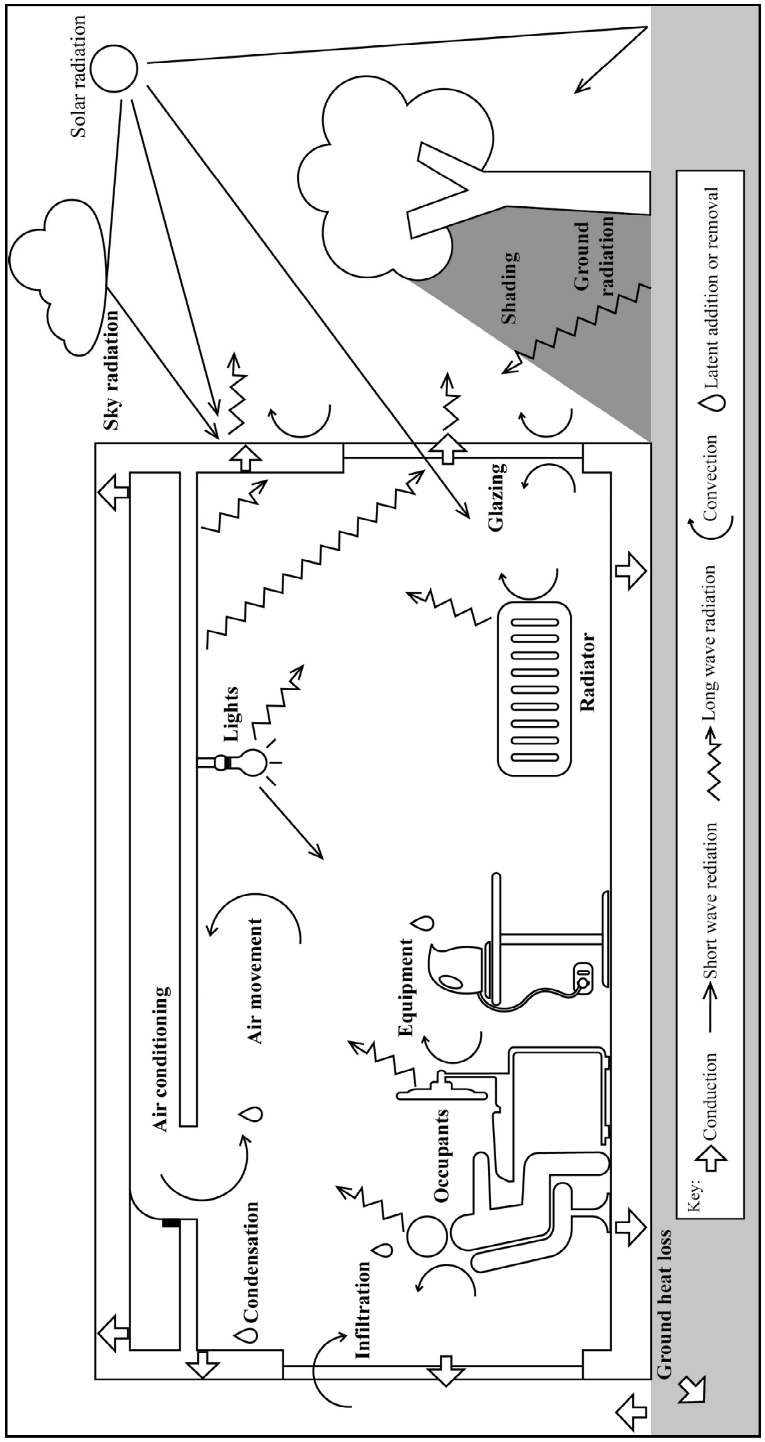

Figure 1-4. Schematic Representation of heat transfer mechanism in a Building.

1.4 Illuminance

Indoor lighting is very important to create an environment suitable for jobs. Although many times the lighting is usually considered to be part of the decorations, lighting can influence the behavior and performance of individuals. Similarly, daylight has been widely studied by many authors. Its study is important because daylight is directly related to the use of energy from the sun. Unless we adopt measures to protect against solar radiation, a high sun exposure can be harmful, especially during spring and summer.

Photometry is the science in charge of the measure the light from the optical point of view, not as radiometry that measures radiant energy in terms of power (including light). Several quantities characterize the light and allow us to study light and brightness. The main ones are explained below.

The luminous flux is the measure of the perceived power of light source; its SI unit is the lumen (lm). The luminous intensity is strongly related with luminous flux, as it measures power emitted by a light in a particular direction per unit of solid angle. The SI unit for luminous intensity is the candela (cd) and it is defined as a lumen per steradian (lm/sr).

Furthermore, the illuminance is the total luminous flux incident on a surface, per unit area. The SI unit for illuminance is lux ($lx = lm/m^2$). In this study, illuminance estimations are made for daylight on a horizontal surface at a given height, which represent a desk where we want the lighting to be adequate to work.

Figure 1-5. shows a point source (luminous intensity = 1 cd) at the center of a sphere of unit radius. The illuminance at any point on the sphere is 1 Ix if the radius is 1 m. The solid angle subtended by the area ABCD is 1 sr (steradian). Therefore the flux density is 1 lm/sr, which corresponds to a luminous intensity of 1 cd as originally assumed. The sphere has a total area of $4 \cdot \pi \cdot m^2$, and there is a luminous flux of 1 lm falling on each unit area. Thus, the source provides a total of 4π lm. (IESNA, 2000)

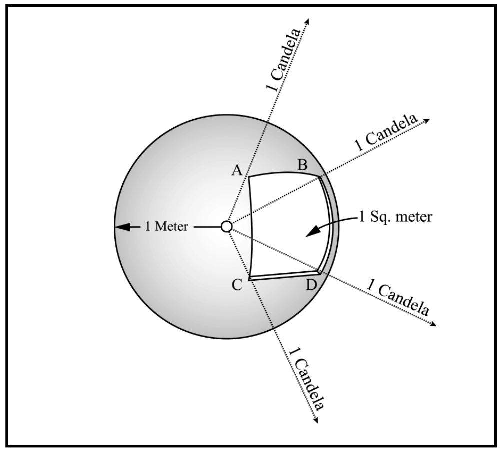

Figure 1-5. Relationship between candelas, lumens and lux. (IESNA, 2000)

The luminance is another luminous quantity; its SI unit is measured in cd/m^2. It is harder to understand because the sphere example does not work to illustrate what it measures. Luminance can be defined as the surface density of luminous intensity that travels in one direction, therefore depends on the location of the receiver (i.e. human eye) and is related to the visual effect that illuminance produces.

The average luminance of the sun is approximately 1600 Mcd/m^2 viewed from sea level. The illuminance on the Earth's surface by the sun may exceed 100 klx; on cloudy days the illuminance drops to less than 10 klx. (IESNA, 2000)

Daylight Performance Metrics

There are several metrics to evaluate the behavior of daylight in the buildings. They can be classified in two groups. The first one corresponds to static metrics, which consider unique sky conditions; and climate-based metrics, which presume different sky conditions. Despite of its limited potential to estimate daylighting, one of the most commonly static metrics used is the Daylight Factor (DF). It is defined as the ratio of the illuminance inside a building to the illuminance at an unshaded point outside the building under an overcast "CIE" sky. This metric requires a defined workplane where the illumination will be measured. Additionally, climate-based metrics also require a defined workplane to assess illumination values, but an hourly climate database is needed as well. The Daylight Autonomy (DA) measures the daylight availability, specifically the annual occurrences of a predefined minimum illuminance levels achieved on a selected workplane. This minimum level usually is desired to satisfy illumination requirements for office tasks, i.e. 500 lux. A newer climate-based metric called Useful Daylight Illuminance (UDI) was developed by Nabil and Mardaljevic (2006). It is defined as the annual occurrence of illuminances across the workplane where all the illuminances are within the range 100 – 2000 lux. These limits are based on reports of occupant preferences and behavior in daylit offices. The advantage of the UDI over the DA is the existence of an upper limit that helps to prevent glare.

1.5 State of the Art

A Swedish study analyzed an office module for 3 different climates in this country. The main objective was to determine the optimal window size to reduce energy demands. The climates correspond to the cities of Lund (lat. 55.72 ° N), Stockholm (lat. 59.35 ° N) and Luleå (lat. 65.55 ° N). The base case corresponds to a building in Lund with clear triple glazing covering 30% of its façade. The annual energy demand for this situation was 68 $kWh/m^2 \cdot year$ for heating and 22 $kWh/m^2 \cdot year$ for cooling. At first, the results show that the orientation of the windows affects the energy demands: the North-oriented office attained the highest demand for heating and the lowest for cooling. The influence of the percentage of the facade glazed proportion on the energy demand was interesting: using a 40% glazed façade instead of 30% increased the cooling demand by 8 $kWh/m^2 \cdot year$, while decreasing the glazed surface from 30% to 20% generates a saving of 8 $kWh/m^2 \cdot year$. Figure 1-6 shows the results obtained by a sensibility analysis of the glass surfaces. According to the results, smaller windows have a lower energy demand for heating and cooling. The best thermal performance is obtained with the lack of glazed surfaces, but windows should be used for the daylight and visual comfort of users. (Bülow-Hübe, 1998)

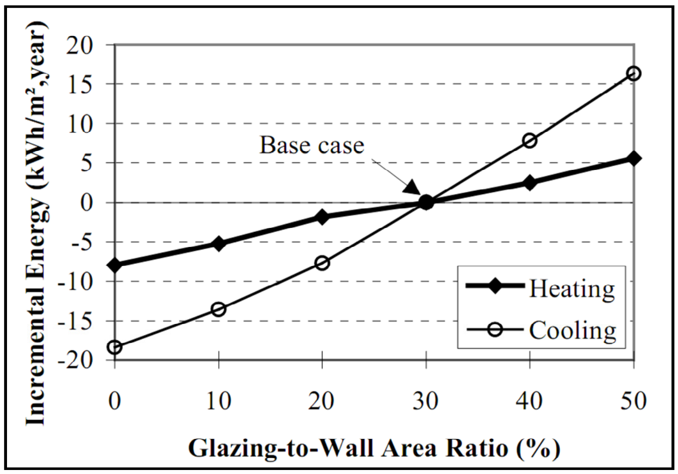

Figure 1-6. Increase of energy demand for different size of windows of an office module located in Lund. (Bülow-Hübe, 1998)

In 2005 research was carried out in Montreal, Canada, studying the impact of design and control of shading devices and the size and orientations of windows on the cooling and lighting load of perimeter offices. The results were calculated for the climate of Montreal using a coupled lighting and thermal simulation module. Figure 1-7 resumes that the results were obtained with the use of automatic shading control and lighting control for a window size of 30% of the façade. The use of this strategy results in a reduction of total annual energy load by 12%, from 6449 MJ (2296 kWh) to 5674 MJ (1576 kWh). The authors also concluded that 30% of glazed surfaces are good enough to guarantee useful daylight on the work area, during 76% of working time. Moreover, they concluded that increased sizes of windows do not produce a significant increase of useful daylight for a South-oriented office. (Tzempelikos & Athienitis, 2007)

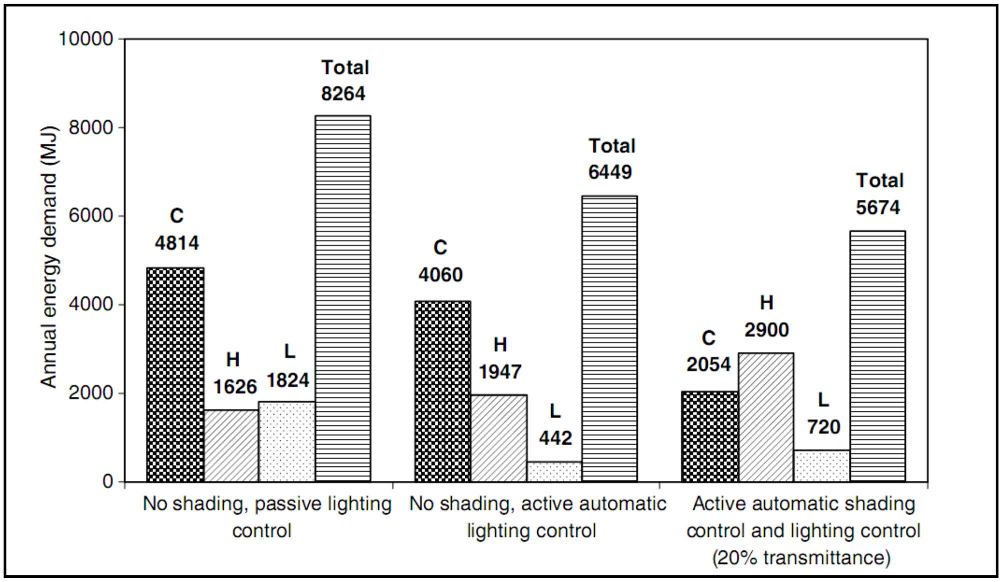

Figure 1-7. Comparison between annual heating, cooling, lighting and total energy load for the 3 cases studied. (Tzempelikos & Athienitis, 2007)

Night ventilation has been proposed as an effective strategy for cooling buildings for the past couple of decades. J. Cook studied the effect of adding thermal mass of high thermal capacity to night ventilation, establishing the effectiveness of this strategy (Cook, 1989). Later studies, conducted by Professor Baruch Givoni, go in the same direction, establishing the possibility of reducing the maximum temperatures reached inside a building environment after using mass combined with night ventilation (Givoni, 1994).

For the application of night cooling of the indoor environment of buildings, the most important climatic parameter that influences its effectiveness is the outside temperature. This parameter determines the potential of the external environment to extract heat accumulated during the day in the thermal mass of the building. This capacity is determined by extracting the difference in temperature between the exterior and interior environments. (Geros *et al*., 2005)

Night ventilation can decrease in effectiveness when applied to urban areas in comparison to rural areas. In London, it was determined that a building located in the rural areas outside of London would have a cooling demand equivalent to 84% of the energy required by an identical building located in the city. Measurements show that the temperature in the city is higher than in nearby rural areas, especially at night, which explains the lower effectiveness of night ventilation in urban areas. The same study indicates that the use of solar protection devices, a proper window size and the reduction of internal gains are important for the efficient use of energy in buildings. It then presents data for two representative weeks, one with hot weather and one with extreme hot weather. For both of the weeks the above strategies were applied without compromising the thermal and lighting comfort for users. For a building in the city, a reduction of cooling demand of 23% was achieved when these strategies were applied during the hot weather week. For the extreme hot weather week a reduction of 40% was achieved. Finally, it is observed that the application of night ventilation reduces the cooling demand an additional 13% for both cases. (Kolokotroni, Giannitsaris, & Watkins, 2006)

In Chile there have been some studies of thermal performance of actual buildings for both periods heating and cooling.

In 2005, a study was conducted to determine the energy demand of the heating and cooling of two buildings using TRNSYS, a dynamic simulation software. Both buildings are located in the city of Santiago; one is located in Vitacura and the other in Providencia. It was determined that the cooling demand is greater than the heating in both cases. In addition, if solar protection in windows and night ventilation are applied, the cooling demand decreases by 58% for the building of Vitacura and 44% for the other. (Bustamante, Espinoza, Jabat, & Solari, 2005)

A prior study conducted in year 2010, based on computer simulations, compared the thermal behavior of two actual office buildings in Santiago. The first building has 9 floors, is located in Providencia and has a mixed façade; about 50% of it is glazed. The second is a 22 floor building located in Las Condes and has a completely glazed envelope (curtain wall) with selective double glazing. We estimated the heating and cooling energy demands using the same properties of the constructive elements of the original buildings. The results of energy demands for the building of Providencia are 13.6 kWh/m^2·year for heating and 23.3 kWh/m^2·year for cooling. If the building is optimized using selective double glazing, external wall insulation, solar protection devices in windows and night ventilation the building can achieve values of 4.4 kWh/m^2·year (-67.6%) for heating and 13.8 kWh/m^2·year (-40.8%) for cooling. Furthermore, the original demands for the building in Las Condes is 1.2 kWh/m^2·year for heating and 60.1 kWh/m^2·year for cooling. After optimizing the building with the use of solar protection on the entire N, E and W façades and night ventilation demands changed to 1.5 kWh/m^2·year (+25%) and 45. kWh/m^2·year (-24.3%), heating and cooling respectively. The main conclusion is that for a climate like that found in Santiago, curtain walls or façades with a large glazed surface will cause a high cooling demand. Additionally it is shown that night ventilation can reduce cooling demand. (Pino, Bustamante, & Escobar, 2010)

1.6 Computer Simulation

A model is a simplified representation of a real system, allowing us to study and obtain results that represent what happens in the original system in a simpler way. This model can be a real scale model of the original system or a virtual model in the computer memory. The simulation is based on the study of a virtual model and its environment under certain parameters of the actual system. Simulation tools have had a powerful development over the last 30 years. Due to the fact that results are even closer to reality and increasingly more reliable, simulation tools have been firmly established in the fields of design and engineering, especially including the study of buildings.

The first steps for building simulations were in the 1960s and 1970s, mainly in the fields of energy, later followed by the fields of lighting, Heating Ventilation and Air-Conditioning (HVAC), air flows, and others. More recently researchers have integrated acoustic and heat transfer, system control and several combinations of situations and environments. In the late 1970s and early 1980s the effort focused on improving code for more versatile, valid and user-friendly tools. During these years the finite element methods were developed, which gained popularity in other fields of engineering, resulting in a set of differential algebraic equations (DAE). Today, simulation tools offer a better interface for the user and a better interchange of data between modules. What aims to reduce inefficiencies in the exchange of data is increasing the speed of model building and subsequent deployment. (Malkawi & Godfried, 2004)

Enclosed with the current capacity of microprocessors, designers are able to generate more complex models and more precise estimates without increasing the simulation running time. This development of computing technology is the prediction of Gordon E. Moore, co-founder of Intel, who proposed that the number of transistors on a chip doubles every 2 years, which reduces manufacturing costs. As personal computers are becoming more powerful, simulation times decrease and consequently reduce the time required for a designer to make a decision during the design process.

All this now allows the use of simulation tools as an effective and economical way to make decisions during the process of building designs that complement the energy efficiency, the comfort of users and the local and global impact on the environment.

1.6.1 Energy Simulation

For the thermal analysis of this study TAS software, from Environmental Design Solutions Limited (EDSL) have been used. This software is of the Building Energy and Environmental Modelling (BEEM) type and works under dynamic state. Moreover, TAS has demonstrated compliance with ASHRAE 140-1 and EN ISO 13791 standards (EDSL, n.d.).

The fundamental approach adopted by TAS traces the thermal state of the building through a series of hourly snapshots, providing the designer with a detailed representation of the way the building will perform either throughout a typical meteorological year or under extreme design conditions.

TAS has three main modules for the whole simulation process: 3D Modeller, Building Simulator and Result Viewer. The first is the tool to develop the geometric model of the building to study. This step considers all dimensions of the different zones, the construction elements are identified and grouped and the location of the building is set to estimate the trajectory of the sun throughout the year and the shadows that are generated.

In the Building Simulator module it is necessary to begin by importing the geometry and then defining all parameters for the simulation. In this set of parameters an hourly weather database is loaded, which should correspond to the location of the building. In addition, properties of building materials, internal gains, ventilation schemes and desired indoor conditions are determined for each area within the building. Later, having all the required information and parameters defined, the simulation is run. It is important to note that modifications can be made in the 3D model and then re-export it to the Building Simulator, where modified parameters are updated in a merged file.

Finally, the file containing the results of the simulation can be reviewed in the Results Viewer module. At this stage you can see the results hourly, daily, monthly or yearly and they can be seen either graphical or tabular. Filters can be applied to visualize only the required information, for either a zone or a specific indicator (e.g. dry bulb temperature). Additionally, the software allows us to export results to a spreadsheet to perform a more specific analysis or to compare results of different simulated cases.

The results from the simulations are considered adequate to meet the scope of this thesis. Essentially, since the main objective is not to calculate the energy demand of a specific building, but to characterize a building in the climatic conditions of Santiago and set a flag that allows the comparison of the different architectural strategies studied. This research is one of the first studies of this type for the environmental conditions of Santiago, so the literature is sparse. However, the results obtained in a previous study for energy demands of two actual buildings with different envelope characteristics are within the ranges acceptable in this field. Alejandro Prieto considered in his Master's Degree thesis the heating and cooling demands of 7 real buildings in Santiago (Prieto, 2011). Prieto's results are the same order of magnitude as those obtained in our previous work. Internal gains values and internal operating conditions are slightly different in both works. See APPENDIX F.

1.6.2 Daylight Simulation

Daylight performance and how to use it properly with efficient use of energy is analyzed by computer simulation. To perform the simulations the software Ecotect, Radiance and Daysim were used.

Autodesk Ecotect Analysis provides a graphical interface where a 3D building can be modeled. Its main characteristics that influence lighting are defined, such as: windows' size, building materials, walls' color, ceiling and floor, use of sun protection and guidance. Ecotect calculates the Daylight Factor on a predefined workplane. However, DF is a static indicator that does not allow an accurate illuminance design. On the other hand, Radiance is a simulation engine that works as backward raytracer and delivers more reliable results than those of Ecotect. Radiance delivers photorealistic renderings of a building. This has been validated by Professor Christoph Reinhart (2006) with empirical testing. The 3D model drawn in Ecotect can be imported to Radiance to perform the analysis and to acquire these renders. However, these results also aim to static sky conditions.

In addition, Daysim was used, a daylight simulation analysis software. This module works based on Radiance simulation engine and has been validated to calculate dynamic illuminance metrics (Reinhart & Walkenhorst, 2001). This software allows, unlike the previous ones, daylight calculations for all possible sky conditions during a year for the building location. Therefore a complete climate database of the specified location is required. The metrics calculated are Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI). The emphasis of this study was done in the UDI indicator, as it allows assessing the fraction of time when daylight is useful for the user, neither too dark (less than 100 lux) nor too bright (over 2000 lux). In practical terms, the simulation of an area of 4 x 4 m requires 4 hours to perform; hence few cases were selected to be analyzed in order to complement the thermal analysis.

1.7 Hypothesis and Objectives

The hypothesis of this research is that in a mediterranean climate, such as Santiago, it is possible to obtain significant energy reductions in cooling energy demand without reducing the comfort of users when architecture and operating strategies are applied. Among these strategies we considered:

- External solar protection. The use of external devices that protect the buildings' façades can reduce solar heat gains generated by sun radiation.
- Adequate sizing of windows. The window's size affects the amount of solar radiation and daylight entering a building. The proper size can avoid problems of overheating and glare.
- Type of glazing. Various types of glass can be found in the market. Each one has different thermal and light transmission properties. Suitable glazing types must be chosen according to the specific requirements of thermal insulation and transparency for a climate like that of Santiago.
- Night ventilation. Due to the high daily temperature fluctuation that exists at this location, night ventilation strategies might help to reduce cooling demand during the warmer months.

The main objective of the study is to quantify and analyze the impact on thermal and light's comfort of users and the energy demand for heating and cooling, by applying separately the different strategies mentioned above. The specific objectives are:

- To use computer simulation to estimate the reduction in energy demands caused by the different strategies used for the same level of thermal comfort.
- To estimate using simulations the temperatures obtained within an office space without the use of energy for air conditioning.
- To evaluate using simulation the lighting performance achieved for different window's sizes.

Finally, it is expected to generate useful information for taking right decisions about the energy efficiency of an office building during the early stages of its design.

2. ARTICLE

2.1 Introduction

Chile is to be found along an extended strip that has a length of around 4.200 km down the south-west coast of South America (17º30′ S to 56ºS), with an average width of 177 km. The climate of Chile is dominated by the massive Andean Range along its eastern edge and the vast Pacific Ocean to the west. To the expected climate variation from north to south, the mentioned geographical features along the entire country causes also pronounced longitudinal climate variation. Santiago is the governmental capital and also the industrial and financial center of the country. The city has a temperate climate with winter rains and very pronounced seasons.

Close to 2.52 million of square meters were authorized to be built up during 2008; it included the Industrial sector, Trade and Financial Institutions inside the Metropolitan Region, and corresponds to a 53.3% of the national total (Instituto Nacional de Estadísticas (INE), 2008). Continuous growing has transformed the city in one of the most modern metropolitan centers of South America, more than a dozen commercial centers and impressive high-rise buildings.

Currently, policies regulating the energy use in office buildings do not exist in Chile; and most design patterns are imported from developed countries, which are not necessarily appropriated for local climate requirements. The development of a country is implicitly linked to the use of energy. Chile is a highly dependent country from the energy point of view. The electricity matrix of Santiago is very poorly diversified; almost 47% of its installed capacity corresponds to hydroelectricity, and the remaining corresponds to thermoelectric sources (Comisión Nacional de Energía (CNE), 2009). During 2008, the national electricity consumption for Public and Trade sectors, in which office buildings are included, was 7,340 GWh. This amount was slightly lower than residential consumption (8,750 GWh) during the same year (Comisión Nacional de Energía (CNE), 2008).

In Chile, usually the cooling demand is higher than heating demand in office buildings. In other countries, several researches have been done in order to study the impact that different architectural strategies produce on the energy demands. An office building study performed in London during 2004 showed benefits in energy use when window size, solar protection, and internal gains were optimized. During two representative weeks, one with a hot temperate climate and the other with an extreme hot climate, 23% and 40% of cooling energy reduction were respectively obtained, once previous modifications were applied. On the other hand, once night ventilation is applied to the optimized building, an additional reduction of 13% is reached. (Kolokotroni, Giannitsaris, & Watkins, 2006)

Many modern buildings have taken advantage of glass transparency in their design to create a clear view to the outside. When using a high window-to-wall ratio (WWR; ratio of the glazed area with respect to the total area of the exposed envelope), occupants commonly might feel thermal and/or visual discomfort and they will apply their own strategies to mitigate this problem. The use of curtains or venetian blinds for example, can minimize visual discomfort, which might change the aesthetic attributes of the building. A study performed in 1998 in Sweden (heating-dominated climate), shows the impact that glazing type and WWR have on cooling and heating demands. The use of modern glazing, with low solar transmittance and U values, can mitigate this problem but it does not necessarily solve it. (Bülow-Hübe, 1998)

On other hand, WWR plays also an important role in natural lighting. It has been studied that working with suitable natural lighting can improve job performance of workers (Heschong, 2002). If glazed areas are very small, it will be necessary to appeal to artificial lighting; but if they are very large, glare can occur. Tzempelikos and Athienitis (2007) studied an office module located in Montreal, Canada, and concluded that a 30% WWR is good enough to guarantee useful natural lighting on the working area, during 76% of working time. Moreover, they conclude that increased sizes of windows do not produce significant increase of useful daylight for a South-oriented office. This study as well has shown an annual energy demand reduction of 12% (2296 kWh to 1576 kWh) for an office with a 30% WWR, automatic shading control and lighting control are applied.

A thermal and lighting analysis of a building located in Santiago, with different transparency surfaces on its façades, is performed in the current study. The main objective is to evaluate the contribution of different architectural design strategies on the efficient use of energy, in order to generate information focused towards taking appropiate decisions in early stages of design. As specific objectives, energy demands for heating and cooling under different design scenarios must be estimated; it is also expected to estimate reduction on energy demand if night ventilation is performed, and to estimate quality indicators for daylight inside an office. In order to generate diverse scenarios, the following parameters are modified: windows size, expressed as Window-to-wall ratio, external solar protection use, use of single, double and selective glazing, office orientation, and night ventilation.

2.2 Methodology

This study aims to analyze the thermal and lighting behavior of an office building of Santiago, for different design conditions, throughout the year. Through computational simulations in dynamic conditions the goal is to combine thermal and visual comfort with low energy use.

For thermal analysis, simulations are performed using EDSL TAS software, under dynamic conditions on an hourly time-series. The software has been validated by means of empiric case comparisons (EDSL, n.d.) and it is scientific and professionally recognized for building dynamic thermal analysis. For natural lighting analysis under dynamic conditions the simulation module Daysim was used, from a 3D office modeled with Ecotect. Daysim module - based on Radiance backward raytracer - has been validated for solar protection use by comparison with empiric results (Reinhart & Walkenhorst, 2001).

Diverse studied parameters and the methodology utilized for obtaining the reported results will be described next.

2.2.1 The Building

The building analyzed in this study was specifically designed to perform a sensibility analysis of results, according to different architectural parameters. It is a 10-floor building, with a square floor (16 m x 16 m); each story contains 12 offices of typical dimensions (4 m x 4 m x 2.8 m height), besides an internal corridor. A 0.7 m enclosure between the ceiling and superior floor was included, in order to consider lighting, ventilation equipments and other installations. Moreover, a stair and lift box was considered, but they were not analyzed in the study. Details of a 3D model done with the thermal simulation software and the floor plant view are shown in Figure 2-1.

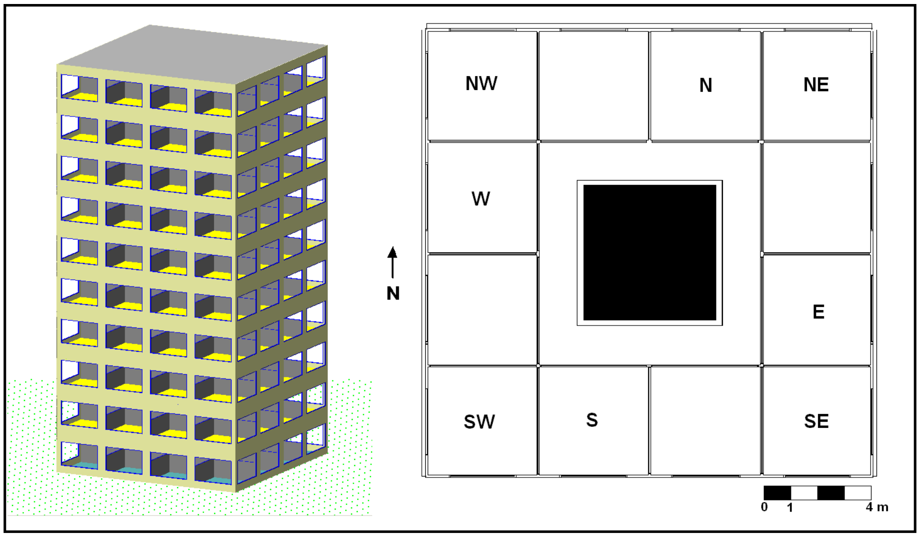

Figure 2-1. Detail of 3D model and plan view of the building used in the research.

A base case is assumed to present the characteristics of the building, which are invariant for the rest of the cases; for instance, constructive elements without considering glasses. This base case considers a glazed area corresponding to a 50% WWR; for this, window size is 3.4 m x 2.06 m, with 4 mm clear single glazing. Each perimeter area (offices) has one window of indicated size, excepting the areas located in the corners, which have one window for each orientation; this implies a twice-glazed surface. Building elements that follow are common for all cases:

- Envelope: reinforced concrete 150 mm thick, with exterior 30 mm thick Expanded Polystyrene (EPS) insulation. U= 1.0 $W/m^2 \cdot K$.
- Internal walls: 1.8 m height, two 12 mm plasterboard layers, with 80 mm mineral wool inside. U = 0.4 $W/m^2 \cdot K$. The objective of these walls is to delimit different areas or zones for the simulation. Because of their heights, a void surface in their superior part is generated, which allows free mass transfers inside this enclosure, corridor, and adjacent areas.

- Ceiling: 10 mm thick plasterboard. U= 4.1 $W/m^2 \cdot K$.
- Floor: reinforced concrete, 200 mm thick. U= 3.1 $W/m^2 \cdot K$.
- Roof: 150 mm of reinforced concrete with 60 mm EPS insulation, 40 mm air separation, and 0.8 mm thick galvanized steel cover. U= 0.5 $W/m^2 \cdot K$.

2.2.2 Climate

Santiago is a part of the Chilean Metropolitan Region. It has a temperate climate with winter rains and a 7 to 8 month long dry season. It is located in the central zone of the country (33º26′16″S; 70º39′01″W), in a valley formed between the Andean and coastal mountains which act as a climate screen. The mean altitude of the city is 570 m.a.s.l.
January is the hottest month and July the coldest one. Mean maximal and minimal temperatures during January are 29.7 ºC and 13 ºC, respectively. For July, mean maximal temperatures are 14.9 ºC and mean minimal are 3.9 ºC (Instituto Nacional de Normalización, 2008). Temperatures below zero ºC are not usually reached. A feature of this climate is that it can achieve up to15 ºC as temperature oscillation between day and night. The mean monthly global solar irradiation, on a horizontal surface, for December and January are 719.7 and 715.1 MJ/m^2, respectively; for July, this value corresponds to 175.2 MJ/m^2. (CNE, PNUD, UTFSM, 2008)

Since the present study considers a dynamic analysis, the climate database needed for simulations is in an hourly time-series and includes: direct and diffuse solar radiation, cloud covering factor, external dry bulb temperature, relative humidity, and wind velocity and direction. The database utilized is the International Weather for Energy Calculations (IWEC), developed by the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE); it is result of the Research Project 1015 and the information which it includes is appropriate to perform building energy calculus based on computational simulations. (ASHRAE, 2001)

2.2.3 Operative Conditions

Internal Gains

Internal gains of offices were estimated for lightning, small equipment, and occupants. Only lightning gain was considered in the internal corridor. Working time includes from 9 AM to 7 PM, Monday through Friday.

Internal gains produced by occupants have been widely studied. A study performed by Chartered Institution of Building Services Engineers (CIBSE), indicates that a man seated and doing moderate work generates 140 W. If this value is normalized for a mixed population where women represent 45% of the total, and environmental temperature is close to 22 ºC, heat emitted by an individual in the same working conditions is 130 W (sensible 84 W + latent 46 W) (CIBSE, 1999). In this study, the office area is 16 m^2 and has been designed for 2 people. Therefore 10.5 W/m^2 sensible heat and 5.75 W/ m^2 latent heat of gains due to occupation, is obtained.

Internal gains due to artificial lightning can be included inside a wide level of values, depending on used lighting technologies. In order to estimate the typical internal gains values in offices, a study was performed in the United Kingdom based on assessments carried out over 30 offices with air conditioned, between years 2000 and 2002. For lightning, internal gains were between 6.2 and 33.9 W/ m^2, with a mean of 12 W/ m^2. The internal gains due to small equipment were also studied; in this case, values fluctuate between 5.7 and 34 W/ m^2, with a mean of 17.5 W/ m^2 (Knight & Dunn, 2003). In present research, a T26 fluorescent light system is assumed for the thermal simulation, which means 11 W/ m^2 in office area, and 7 W/ m^2 in the corridor for lightning gains. Offices with larger WWR are likely to require less artificial lightning compared with those of smaller WWR. Although in this study the gains due to artificial lighting are identical for all different sizes of windows because the magnitude order of this value can be less relevant compared with heat gains due to solar radiation. Two laptop computers of 90 W power are considered as small equipment. It is assumed that they transform all energy in heat and for the 16 m^2 area of each office, internal gain obtained is 11.25 W/ m^2.

Ventilation and infiltrations

For thermal simulations a mechanical ventilation system for requirements standards during working time (9 AM to 7 PM) has been assumed. ASHRAE suggests that one person working in an office requires 10 l/s (36 m^3/hour) of exterior air (ASHRAE, 1999); during this study, 8 m^2/person (22.4 m^3/person) were considered. On the basis of the standard previously suggested, ventilation of 1.28 air changes per hour (ach) is required.

There exists literature on several methods developed to calculate building infiltrations; however, most of them do require empirical data on effective infiltration area and/or air flow or stack effect (ASHRAE, 2009). As this is not available information and results of the present study do not seek to design an air conditioner system, infiltration has been estimated from empirical data proposed for offices by CIBSE (2006). The infiltration value used in simulations is 0.3 ach for all building areas.

<u>Thermal comfort</u>

Thermal comfort can be defined as physical and psychological wellness of an individual when temperature, humidity, and air movement conditions are favorable for the activity that has to be developed. Environment users have the tendency to change their behavior, modify environmental conditions or both, in order to feel comfortable. Diverse studies have stated common zones of comfort, where a high proportion of users should feel comfortable. The heat balance proposed by Fanger for thermal comfort estimation considers clothing as part of users' behavior (Fanger, 1970). ASHRAE also considers season suitable clothing and states a comfort zone inside a psychrometric diagram. Physical activity is also taken into account. For the current case, a seated person performing sedentary activity has been considered. For thermal simulations the following comfort ranks have been considered: for summertime, temperature between 23 and 26.5 ºC and relative humidity of 30-70%; for wintertime, temperature from 20 to 23.5 ºC and relative humidity below 65% (ASHRAE, 2001).

2.2.4 Thermal Analysis

The methodology is based on the analysis of different cases, each one having particular variables. Starting with a base building, different modifications and simulations throughout the year have been done in order to evaluate building thermal behavior in different periods of the year. For this study 288 cases are simulated, in which four variables are modified: Window-to-wall ratio (WWR), lack of or type of external solar protection devices, glazing type and orientation. However, the floor plant of designed building does not have its 12 offices in the same orientation; therefore, there are only 36 simulations of the complete floor (12 offices distributed in 8 orientations + corridor). Specifically, the 6th floor located approximately in the middle part of the building, was considered. Variable details can be seen in Table 2-1.

Table 2-1. Description of variables for the simulation. By combining the different variables 288 cases for an office module are studied.

Variables	***Possible values***
Window-to-wall ratio	20% 50% 100%
Types of solar protection devices	No solar protection Overhang in N and blinds for E and W orientations Blinds in N, E and W orientations
Type of glazing	Clear single glazing Selective single glazing Clear double glazing Selective double glazing
Orientation	North Northeast East Southeast South Southwest West Northwest

As suggested by its name, the window-to-wall ratio indicates the glazed proportion of the total building envelope. The remaining surface is assumed to have reinforced concrete, as indicated in section 2.2.1 among building`s envelope characteristics.

Multiple types of external solar protections are available in the market; however, for present study only 2 types were considered as lack of solar protection as well. Three variables for solar protection are: i) no protection; ii) horizontal blinds (HB) in E and W orientation, and N-oriented overhang (OH); and last, N, E, and W oriented horizontal blinds. The OH has been designed to avoid direct solar radiation in this location (33 ºS) from September 21st through March 21st (Southern hemisphere equinoxes). Therefore, there are 3 OH sizes, each one corresponding to one window size and utilized only for this case. Horizontal blinds are thin fin arrangements (66 mm wide, 55 mm distance between fins and length according with windows width) can be easily founded in the specialized market. It is considered that they completely cover the façade glazed surface.

Glazing technology has been developing over the years. Single, double, and three-layered glazing are currently available; also adhesive layers and dyed glazing have been developed, which allow creating specific shades and selectivity against solar radiation. In this study, four glazing types are used: i) clear single glazing (SC), ii) selective single glazing (SS), iii) clear double glazing (DGC), and iv) selective double glazing (DGS). Properties of each glazing type are indicated in Table 2-2.

Table 2-2. Types of glazing and their main optical and thermal properties. ST means solar transmittance and LT means light transmission factor.

Type of glazing	*Thickness, mm*	*ST*	*LT*	*U Value, $W/m^2·ºC$*
SC	4	0.82	0.9	5.82
SS	5.85	0.5	0.6	5.74
DGC	4 (inside) + 15 + 4	0.68	0.82	2.78
DGS	4 (inside) + 15 + 6	0.41	0.54	2.76

Base Case

Buildings with single glazing as well as others without environmental conditioning system still exist in Santiago. In order to evaluate internal conditions in a building without climate control, a simulation was carried out for conditions inside the base case building. Preceding variables were established as follows: 50% WWR, lack of solar protection, and clear single glazing (SC) for the 8 orientations. Additionally, clear double-glazing (DGC) use was also studied. Simulations assume that no heating or cooling systems are applied; the goal is to know the inner temperatures that can be reached inside an office without energy use.

Energy Demands

This corresponds to the most important section of the study. Energy demand for heating and cooling were estimated for all mentioned cases, modifying input parameters. In this way, building performance (energy demands) can be estimated for a group of established variables.

Furthermore, offices presenting more adverse conditions from the thermal point of view can be visualized within the same floor, depending on its orientation.

Once all results are obtained a sensibility analysis can be performed. The aim is the building optimization in order to be more efficient for the energy use point of view. Based on this analysis, how dependant is energy demand in respect to certain variable may be observed. Thus, Guidelines for architectural design can be determined.

Night Ventilation

Night ventilation can be not taken into account as a design strategy, but can be considered during basic steps of this process, in order decrease cooling energy demand in buildings. The use of night ventilation is estimated as appropriate for buildings without night occupation, like offices buildings, and for a high temperature fluctuation climate during cooling periods of the year when over comfortable temperatures are reached during the day and relatively low temperatures occur at night, as it occurs in Santiago. To be implemented, ventilation by windows opening and/or by mechanical systems can be selected, specifically if safety problems must be considered.

In this study, mechanical night ventilation is assumed, since it is more controlled and does not depend on users' behavior, regarding windows opening. Analysis was carried up only to some representative cases, which allow performing a general comparison of night ventilation benefits.

Night ventilation period was restricted to cooling period, including October and March. Selected time is from 10 PM until 7 AM next day, from Sunday to Friday.

Studies have been done on usual values for a suitable air turn over rate that permits good ventilation. As long as ventilation flow increases, heat extraction is higher. However, from 25 ach the effect stabilizes and flow increase does not produce a marked benefit (Bustamante W. , 2007). For this specific study, a ventilation rate of 8 ach was considered.

2.2.5 Daylight Analysis

An annual daylight analysis was performed throughout computational simulation to study the visual comfort of users; it allows knowing the availability of daylight inside an environment based on different performance metrics.

Daylight Performance Metrics

Currently, dynamic and static factors have been developed. Daylight Factor (DF) which indicates the relation between horizontal illuminance on a point inside the building and exterior horizontal illuminance on a perfectly clear point, is still used; it applies for a CIE (International Commission on Illumination) designed cloudy sky. The main constraint is that it corresponds to a static factor and does not consider climate conditions, neither building location. Daylight Autonomy (DA) defined as the time fraction along the year, in which minimal illuminance wanted on a pre-determined surface is reached (usually, for office work 500 lux are required) is among dynamic factors. It needs location information and hourly climate data, besides orientation and geometry of the room to be analyzed. Glare problems can occur if the façade receives too much solar radiation or has a big glazed area. For this reason, Mardaljevic and Nabil (2006) propose Useful Daylight Illuminances (UDI), which like DA, considers desired illuminance during a fraction of working time; but in this case it provides a superior limit to avoid glare. Proposed range (between 100 and 2000 lux) is based on users working preferences reported by same authors, where useful illuminance is not very dark (<100 lux) and neither very brilliant (>2000 lux).

Simulation Parameters

For daylight analysis it aimed to study light incidence on a desk or working surface; therefore, a 36 node horizontal grid was fixed at 80 cm height from ground floor. Simulation was done for a simplified office of the proposed building considering principal different orientations and diverse cases of solar protection. Daylight analysis was done only for selected cases, not for all of them. The working time established is from 9:00 AM to 7:00 PM and the climate database is the same used for the thermal study.

2.3 Results

2.3.1 Inside Temperature

Results obtained for base case building (50% WWR, clear single glazing, without solar protection) are rather deficient. It generates thermal discomfort for users or high energy demand for air conditioning. If a typical January day (max Tº 33 ºC – min Tº 14 ºC, clear sky) is analyzed, overheating occurs in all orientations. It is also observed that thermal inertia of the building is high, and even if the environmental temperature is low during the night, heat cumulated along the day is not dissipated. Thermal conditions and temperature evolution along the day are showed in Figure 2-2, for four selected offices.

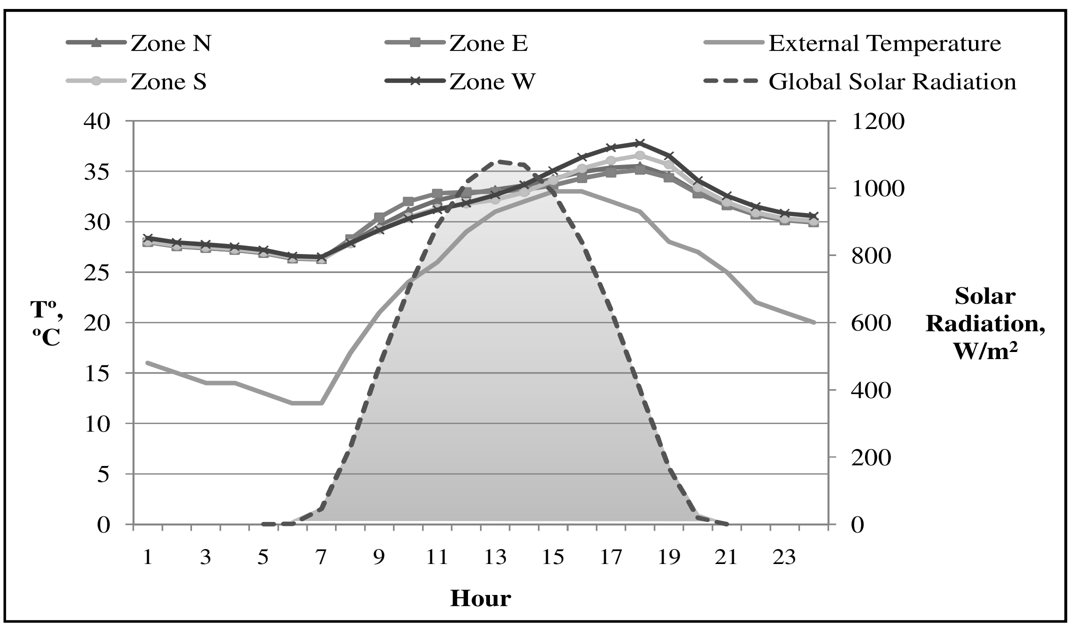

Figure 2-2. Temperature evolution inside offices during a typical summer day, when outside dry bulb temperature ranges from 14ºC to 33ºC and clear sky conditions are registered for a building with 50% WWR.

Moreover, thermal insulation of the indicated building´s envelopment was improved by means of double clear glazing. By doing this, building thermal inertia was favored. During summer time results are worst than for the previous case. It can be seen that overheating can occur even during the winter. During a clear sky day and 20 ºC maximal environmental temperatures, internal gains plus solar gains can be sufficient enough to require environmental cooling. Again, offices oriented in the four main directions were analyzed and inside temperature evolution along July´s days are plotted in Figure 2-3.

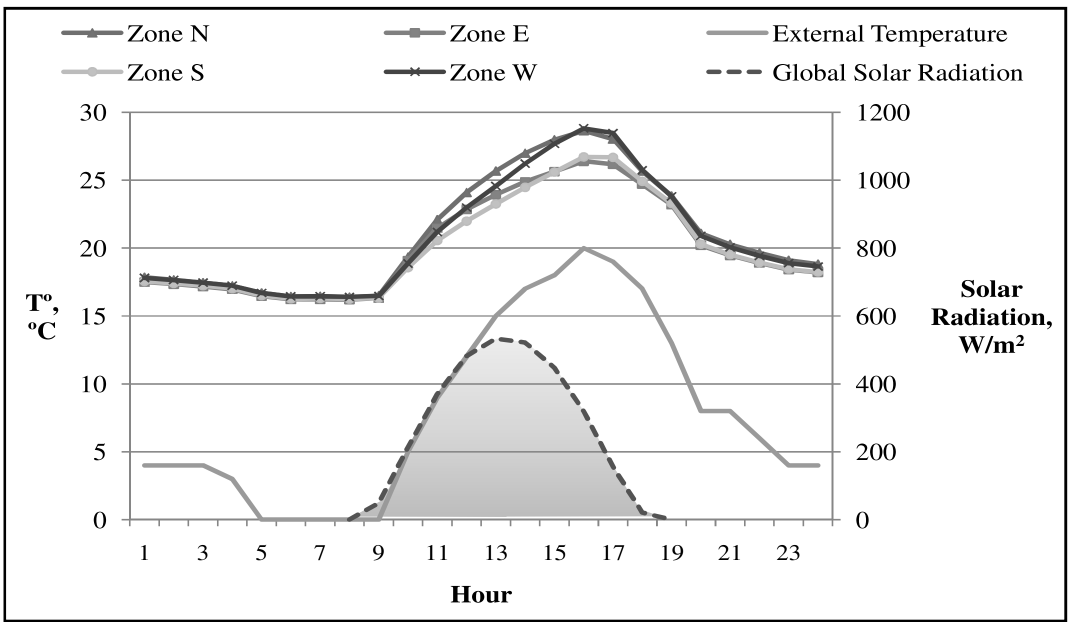

Figure 2-3. Temperature evolution inside offices during a winter day with clear sky conditions and external dry bulb temperature from 0 ºC to 20 ºC, for a building with 50% WWR.

2.3.2 Thermal Analysis

Results for 288 cases were grouped for the 12 offices per floor obtaining 36 different cases. For each of these 36 cases, including the 12 offices plus the corridor, annual energy demands were normalized by the total area of the floor. In this way, considered variables are the previous but orientation is considered for the 8 main directions per floor (N, NE, E, SE, S, SW, W and NW). Input parameters that are common to all cases are shown if APPENDIX A.

The most influential parameter on energy demand is the WWR. Independent of glazing and the solar protection type used, a building with low WWR (20%), will obtain a demand lower than 40 kWh/m^2·year. With 50% WWR, the energy total energy will fluctuate between 40 and 70 kWh/m^2·year. Finally, for a 100% WWR will fluctuate between 50 and 155 kWh/m^2·year. Higher WWR increase energy demand variability because it is less insulated and allows higher solar gains than concrete with external insulation. Figure 2-4 shows the mentioned results in box plots. In this plot, the darker and thick line inside boxes represents mean of each sample. Besides, this graph type allows us to know the variability average showed by each sample. Included between external extremes of branches we may find all sample results and inside the boxes, 50% of them. Results are shown in quartiles: two quartiles over the mean and two below it, delimited by extremes of boxes and branches.

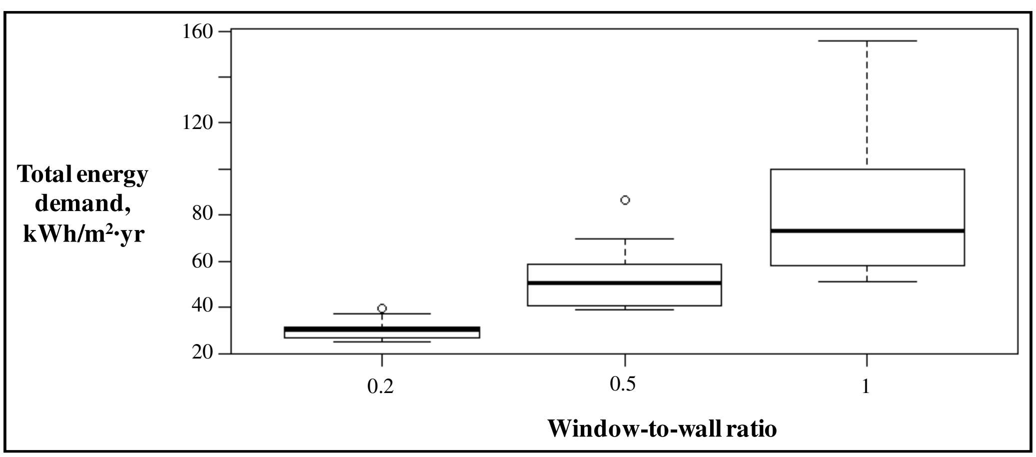

Figure 2-4. Box plot of total annual energy loads with respect to window-to-wall ratio (WWR).

Figure 2-4 shows that the lower the WWR is, the lower is the annual energy demand. Besides it is shown that the higher the WWR is, variability of total energy demand is also higher.

If sample means, grouped by solar protection type, are compared with cases without solar protection, it is observed that this strategy can reduce energy demands in around 30% and can reduce variability of the samples values. However, the WWR is the dominant variable. A significant advantage cannot be noticed between the two types of solar protection studied, as is observed in Figure 2-5.

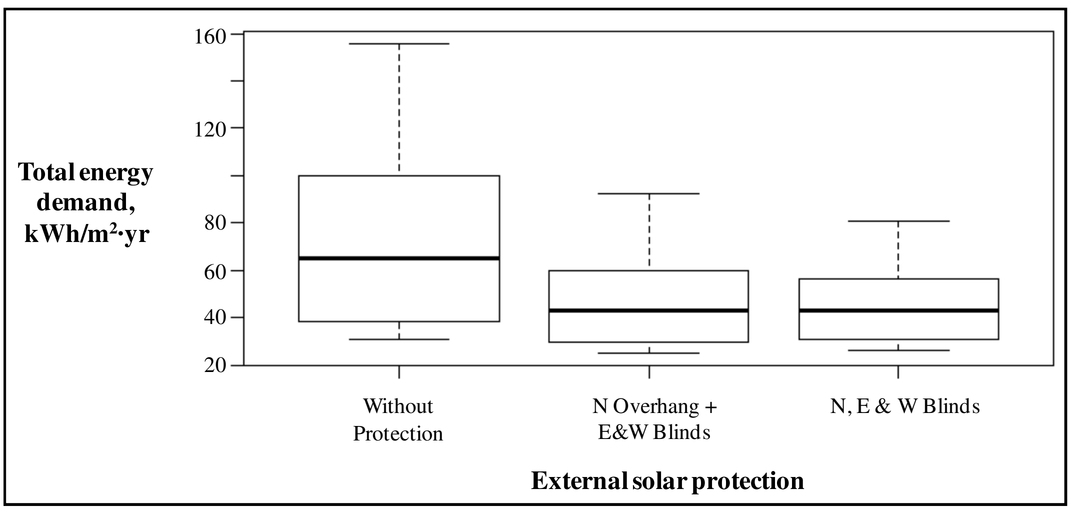

Figure 2-5. Box plot of total annual energy demand with respect to use of solar protection devices.

Glazing type is the third variable studied and does not generate significant difference. The reason is that in Santiago winter temperatures are not very severe, so if windows are small (WWR of 20% or lower) it might not be a must to utilize double or triple glazing; however this is recommended to improve the building efficiency. The glazing type that can increase energy demands particularly during summer is the clear double glazing (DGC). This problem can be mitigated if some solar selectivity type (DGS) is applied, as observed in Figure 2-6.

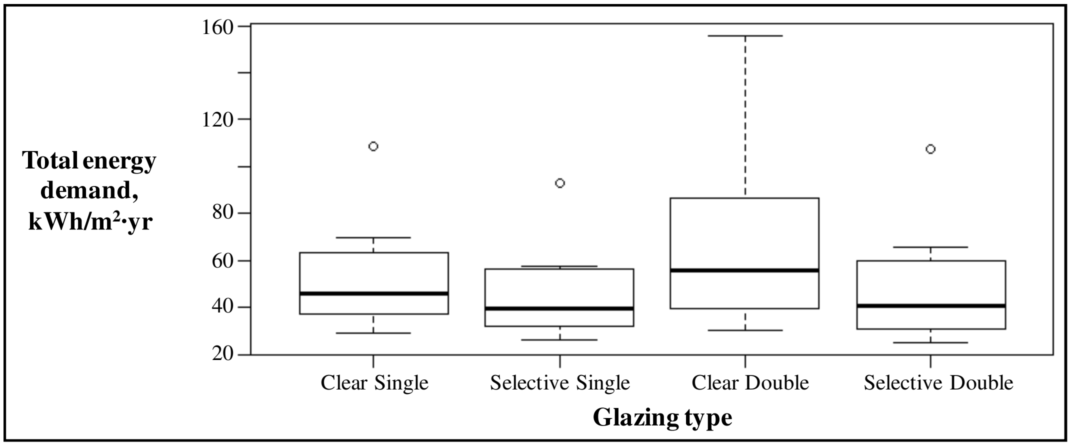

Figure 2-6. Box plot of total annual energy demands with respect to glazing type.

The less efficient configuration has been sought among studied cases. The completely glazed façade building with DGC and lack of solar protection shows higher problems, mainly during summer. In a cooling energy demand point of view, most critical orientations are north and west oriented due to their high solar gain through windows. In fact, for the less efficient configuration the office located at Northwest corner has an annual cooling demand of 194.9 kWh/m^2·year; and the lowest cooling demand is 120.8 kWh/m^2·year for a South-oriented office. Demands can be decreased if glazing has some level of solar selectivity. However using selective glazing is not enough to reduce cooling energy demand, as can be observed in the color plot for cooling demands of offices with fully glazed façade without solar protection devices shown in Figure 2-7.

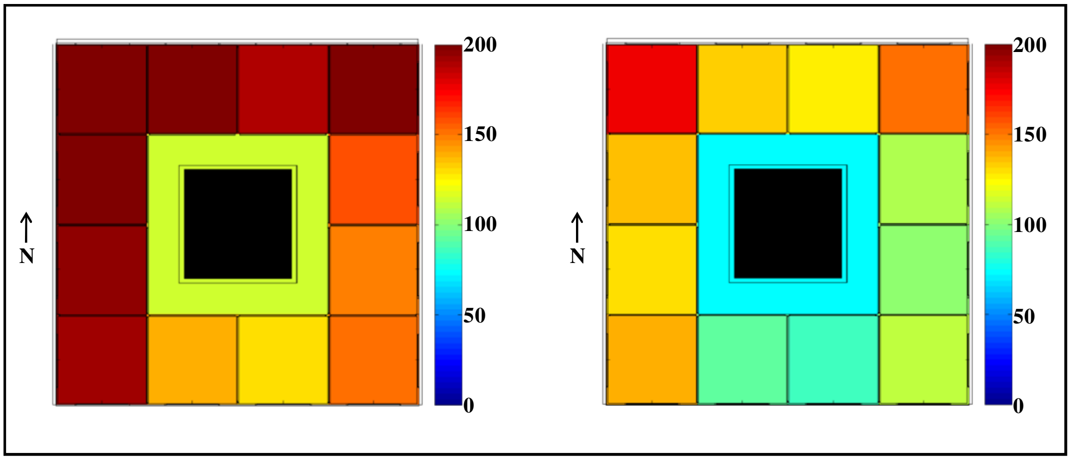

Figure 2-7. Color plot for cooling demand of offices with fully glazed façade (100% WWR) without solar protection devices. Left plan view corresponds to a building with clear double glazing (DGC). On the right DGC has been replaced by selective double glazing (DGS).

Among the studied cases the most efficient corresponds to the 20% WWR building, with selective double glazing, North oriented overhang (OH), solar protection, and horizontal blinds (HB) on East and West oriented windows. It generates a thermal status which registers no significant differences between different oriented offices. In cooling periods the most demanding office is the North-West-oriented with 19.6 kWh/m^2·year, and the less demanding is South-oriented with 13.9 kWh/m^2·year. The mean heating demand is 3.1 kWh/m^2·year. For the entire floor (12 offices + corridor) total annual energy demand reach 25.2 kWh/m^2·year. Besides, it was considered to analyze the optimal case but using simple selective glass; in this case heating demand slightly increases with a mean of 5.7 kWh/m^2·year, for the 12 offices; cooling demand slightly decreases during summer. Again, during cooling periods NW and South-oriented offices have extreme energy demand with 16.5 and 11.4 kWh/m^2·year, respectively.

2.3.3 Night ventilation

Night ventilation seems to be an effective strategy to decrease cooling load because of the high temperature oscillation in Santiago. Six of 36 cases of entire floor have been selected to perform the analysis. Results show that night ventilation of 8 ach applied between 10 PM and 7 AM can reduce up to 35% of cooling demand. Heating demand is slightly increased in most cases. This is due to a deficiency of the utilized method since night ventilation is also applied in transition periods between winter and summer where heating could be also required. This increase in heating demand could be avoid with a better planning of night ventilation, which is not considered in the method applied.

The main benefit of night ventilation is that it allows for effective heat dissipation throughout mass interchange. This is very useful for well insulated buildings or for those that, because of their building materials, present much mass and thermal inertia. For those buildings with mostly glazed facades (50% to 100% WWR) night ventilation is not an effective strategy to dissipate the heat gained through solar radiation.

For the case selected as optimal thermal behavior (20% WWR; North OH + E and W HB; DGS) an additional 37% of reduction is obtained for global demand (cooling + heating), achieving energy demand of only 15.9 $kWh/m^2 \cdot year$. Figure 2-8 shows summarized reductions obtained for the 6 selected cases.

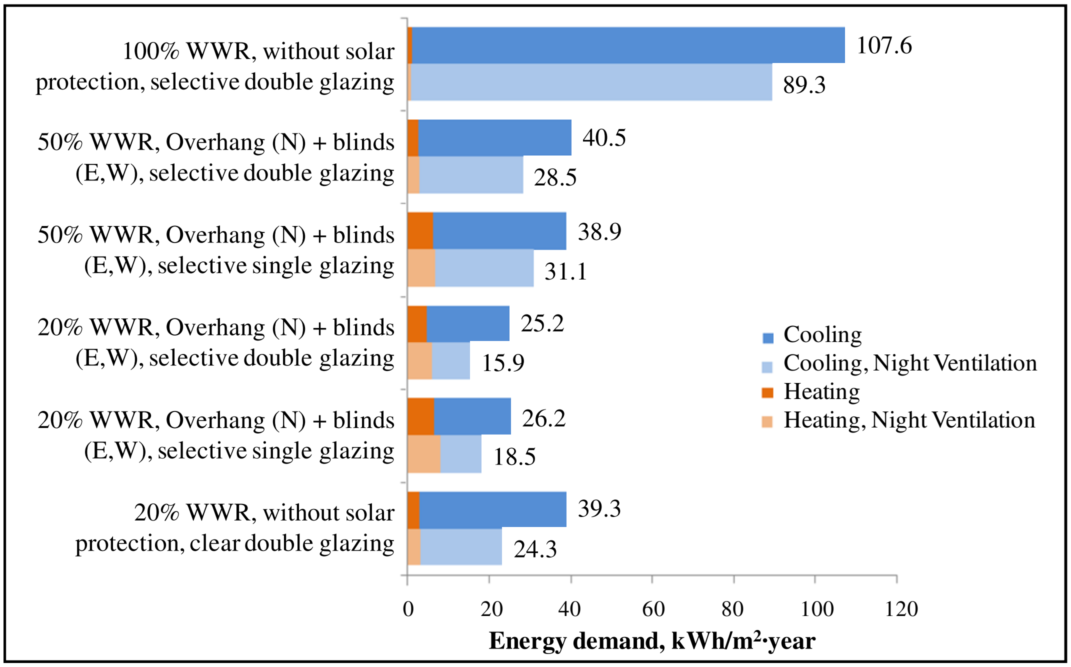

Figure 2-8: Energy demand for selected cases when night ventilation is applied.

2.3.4 Daylight analysis

The case selected as optimal thermal behavior considers windows covering 20% of the total façade, besides inclusion of solar protection and selective double glass. It can be thought that this would transform the office in a dark place to work, but actually, lighting proceeds in a good way. Based on the UDI metric simulation results, S and SW-oriented offices show useful illuminance (between 100 and 2000 lux) during more than 80% of working time. For other orientations a mean useful illuminance over 60% of working time is obtained. An excessive (>2000 lux) or a very low illuminance (<100 lux) for office work performance occurs during the remaining time. E and W orientations have horizontal blinds (HB). These 2 orientations do not exhibit excessive illuminance but low illuminance almost during 20% of working time. For remaining orientations there is low illuminance between 6 and 7% of time, and excessive illuminance depends on orientation. In those points where illuminance exceeds 2000 lux glare may occur. Results for main orientations are shown in Figure 2-9, for UDI indicators between 100 and 2000 lux, and for those higher than 2000 lux. High standard deviation is observed in both figures and less representative points over the grid can be observed. The reason for this is that illuminance is not uniform over the whole surface. There exist surfaces where direct radiation falls during summer, others on which it falls during winter and some which do not receive direct radiation at all. As the analysis is dynamic for the whole year, it considers climate time variables which are not completely uniform.

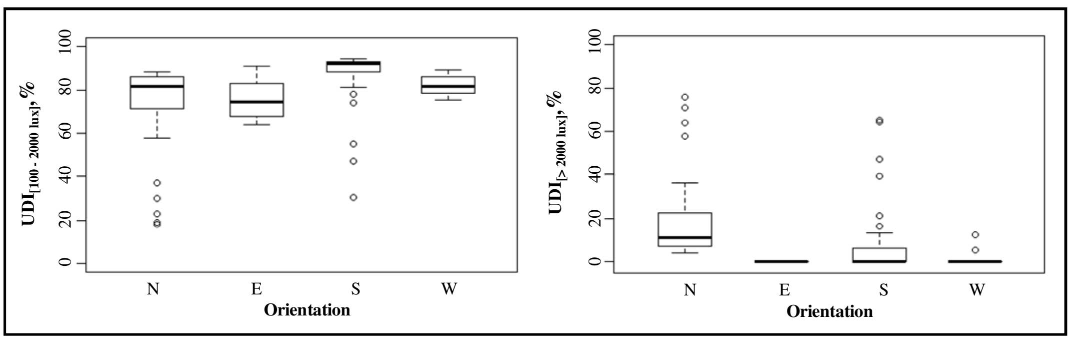

Figure 2-9. UDI values obtained for main orientation. Left plot shows UDI values between 100 and 2000 lux. Right plot shows UDI valued where illuminance exceeds 2000 lux.

2.4 Conclusions

Described results allow observing the occurrence of several phenomena inside offices, which are not deduced during a first inspection. The main contribution of this work is to establish that computer simulation is an effective tool for building design when characterizing their energy behavior. This helps in the identification and correction of future problems in a wrongly designed building, before its construction and operation. The design of a building must consider habitability conditions of the final user and necessary energy to reach these conditions. From the present study, the following main conclusions were obtained:

1) For a climate like Santiago´s, with low cloudiness during spring and summer and very hot (over 28ºC) temperatures occurring during the day, overheating in office buildings may occur in all the analyzed orientations. This phenomenon is very probable when some part of the building façade is glazed and if glazing lacks solar protection or solar selectivity. It is almost a fact that there exists summer overheating in buildings having 100% WWR; it probably also occurs during winter if sky conditions are clear and environmental temperatures are close to 20 ºC. Therefore, it is recommended to reduce the windows size in the orientations studied, in order to avoid this phenomenon; otherwise, a high energy demand will be needed to cool the environment and achieve comfortable conditions for users.

2) Important variability on energy demand is produced if using large glazed areas. It is important to pay attention to the glass type utilized, specifically if it corresponds to an important area of the façade. High heat loss due to conduction will occur during the winter if the glazing is simple. On the other hand, heat loss is smaller during winter if the glazing is double-layered, but it is still higher than the loss throughout an isolated concrete wall, due to its higher U value. Therefore, a mixed façade gives better results during colder months. During summer simple or double glazing is prejudicial since it

permits income of visible spectrum of solar radiation, but does not leave infrared spectrum (heat) to escape. Solar gain is lower if glass has selectivity, but it is still important. Therefore, for summer time better results than with 100% WWR are also obtained with mixed façades.

3) From 288 studied cases the most influent factor on energy demand (heating and cooling) is the size of glazed surfaces. If the WWR is 20%, any of the studied building configurations will reach a global energy demand lower than 40 $kWh/m^2 \cdot year$. This happens with or without solar protection and independently of the glazing type selected. If the mentioned ratio is 50%, energy demand will be located between 40 and 70 $kWh/m^2 \cdot year$. Finally, if the whole façade is glazed (100% WWR), demand will be between 50 and 155 $kWh/m^2 \cdot year$. It is important to notice that if size of windows is properly dimensioned the orientation of the office is not relevant to reach less energy demand. The best performance is obtained using small windows (20% WWR), North-oriented overhangs, and East and West oriented horizontal blinds, besides selective double-glazing. If selective single glazing is used, the heating demand will increase slightly, but cooling demand decreases in summer; so, this is also a good alternative to avoiding the additional costs represented by selective double-glazing.

4) External solar protection can be useful and its importance is higher if the glazed area is larger. For both solar protection types studied, energy demand is lower than for cases without protection. Similarly, utilization of solar selective glazing gains importance if more glazing is used in the façade. In general, the benefit obtained during the summer with this type of glazing is superior to the winter detriment for the decreasing of the solar benefit. This can be amended with the use of double-glazing, which has less heat loss by conduction than single glazing.

5) Night ventilation is shown as an effective operative strategy to reduce the cooling energy demand for Santiago's climate type; this, mainly because of the significant temperature oscillation between day and night. For an office building like the one studied, ventilation of 8 ach from 10:00 PM to 7:00 AM during working days can reduce up to 37% of total annual energy demand needed for air conditioning. For this, night ventilation can act as a good operative strategy for an already constructed building, even if it does not solve problems arising from bad initial design.

6) Finally, correct utilization of natural light can positively act on a user's comfort, besides the reduction of artificial lighting use which generates an internal gain of heat and increase in electricity consumption. Satisfactory results are obtained for the light behavior inside an office correctly behaving from the thermal point of view. Considering a 20% WWR, selective glazing use and solar protection over 4 main orientations, daylight on the working area is suitable for an 80% mean of working hours for North, East and West-oriented offices, and for almost 90% of time for South-oriented offices.

Further Work

The main reason Santiago was chosen for this study is because of its important population respecting the country's total. However there are also several main cities in Chile, with different climates, where offices buildings are rapidly developing. It might be interesting to extend this research to other climates and evaluate the influence of the architectural strategies in energy demand. Because the emphasis of this investigation was on estimating energy demand, its scope excludes interactions with the HVAC system. The efficiency of heat transfer of a heating system is usually higher than the efficiency of a cooling system, so HVAC system must be considered to estimate electricity consumption and its cost. As a final point, energy demand and lighting are closely related. Many researchers have specialized in one field, but only few have studied both energy demand and lighting. More integrated studies should be performed to achieve better results in luminic and thermal comfort for users with the minimum use of energy.

Acknowledgments

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APPENDICES

APPENDIX A: INPUT PARAMETERS

Table A-1 shows the input parameters used for energy demands estimations and that are common to all cases simulated in TAS.

Table A-1. Input parameters for building energy simulations.

Simulation Parameters	
Climate data base	International Weather for Energy Calculations. Santiago, Chile.
Cooling Period	October – March
Heating Period	April – September
Working Time	Monday – Friday, 9 AM – 7 PM
Ventilation	Rate: 1.28 ach
Infiltration	Rate: 0.3 ach
Occupation heat gain	Offices: 7.5 W/m^2
	Corridor: 0 W/m^2
Equipment heat gain	Offices: 11.25 W/m^2
	Corridor: 0 W/m^2
Lighting heat gain	Offices: 11 W/m^2
	Corridor: 7 W/m^2
Comfort temperature	Cooling period: 23 – 26 ºC
	Heating period: 20 – 23.5 ºC
Night ventilation (when applied)	10 PM – 7 AM Sunday night – Friday morning
	Rate: 8 ach

APPENDIX B: HEATING AND COOLING DEMAND

The results for the cooling and heating demand for the 6th floor of the studied building are shown in Table B-2. Each energy value corresponds to the sum of the 12 offices and the corridor demand divided by the total floor surface.

The nomenclature used means the architectural strategies applied for each case are detailed in Table B-1.

Table B-1. Nomenclature for architectural strategies.

AXXX	Glazing Ratio	20: window-to-wall ratio = 0.2
		50: window-to-wall ratio = 0.5
		100: window-to-wall ratio = 1
BX	External Sola Protection	1: Without solar protection
		2: North Overhang + East & West horizontal blinds
		3: North + East & West horizontal blinds
CX	Glazing Type	1: Clear single glazing
		2: Selective single glazing
		3: Clear double glazing
		4: Selective double glazing

Table B-2. Heating and cooling energy demand for the studied floor.

Case #	**Nomenclature**			**Heating kW·h/m²·yr**	**Cooling kW·h/ m²·yr**	**TOTAL kW·h/ m²·yr**
1	A20	B1	C1	5.42	31.85	37.3
2	A20	B1	C2	5.70	26.31	32.0
3	A20	B1	C3	2.81	36.50	39.3
4	A20	B1	C4	4.03	26.71	30.7

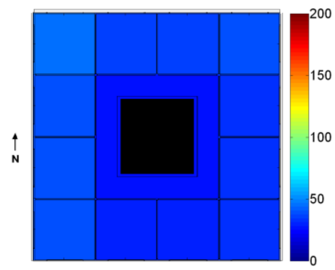
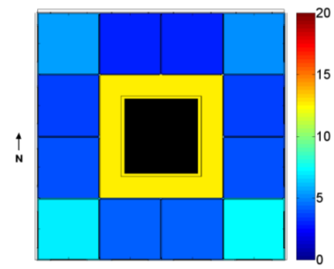
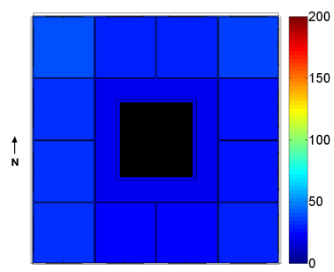
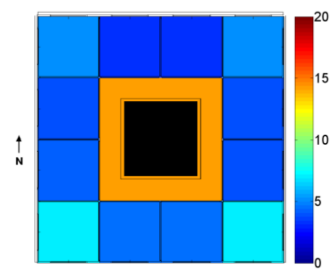
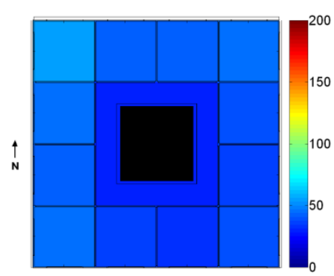
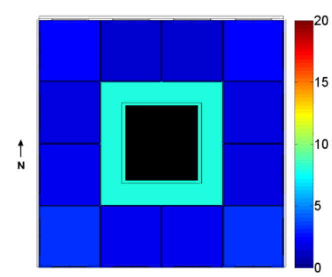
Case #	Nomenclature			Heating kW·h/m²·yr	Cooling kW·h/ m²·yr	TOTAL kW·h/ m²·yr
5	A20	B2	C1	6.35	22.64	29.0
6	A20	B2	C2	6.57	19.66	26.2
7	A20	B2	C3	3.39	26.64	30.0
8	A20	B2	C4	4.65	20.56	25.2
9	A20	B3	C1	7.76	22.90	30.7
10	A20	B3	C2	7.72	19.84	27.6
11	A20	B3	C3	4.44	26.77	31.2
12	A20	B3	C4	5.56	20.71	26.3
13	A50	B1	C1	4.87	64.60	69.5
14	A50	B1	C2	4.56	52.78	57.3
15	A50	B1	C3	1.02	85.75	86.8
16	A50	B1	C4	1.72	58.34	60.1
17	A50	B2	C1	6.81	38.09	44.9
18	A50	B2	C2	6.25	32.69	38.9
19	A50	B2	C3	1.70	53.84	55.5
20	A50	B2	C4	2.65	37.88	40.5
21	A50	B3	C1	8.59	37.34	45.9
22	A50	B3	C2	7.72	31.96	39.7
23	A50	B3	C3	2.57	52.19	54.8
24	A50	B3	C4	3.61	36.93	40.5
25	A100	B1	C1	6.19	102.63	108.8
26	A100	B1	C2	4.87	87.88	92.8
27	A100	B1	C3	0.67	154.94	155.6
28	A100	B1	C4	1.00	106.56	107.6
29	A100	B2	C1	8.67	54.45	63.1
30	A100	B2	C2	6.71	49.37	56.1
31	A100	B2	C3	1.20	91.19	92.4
32	A100	B2	C4	1.65	63.97	65.6
33	A100	B3	C1	10.21	47.46	57.7
34	A100	B3	C2	8.01	43.00	51.0
35	A100	B3	C3	1.99	78.47	80.5
36	A100	B3	C4	2.52	55.65	58.2

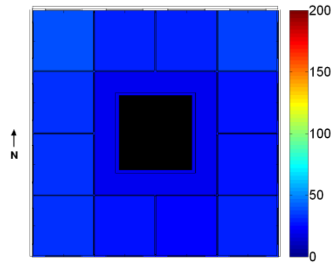
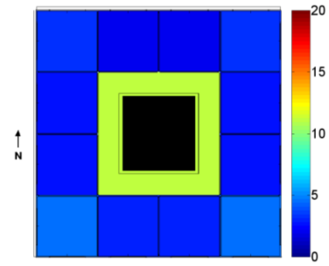
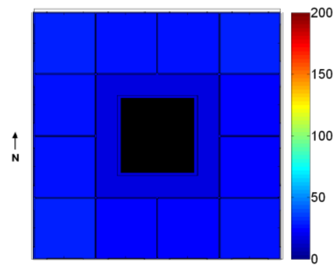
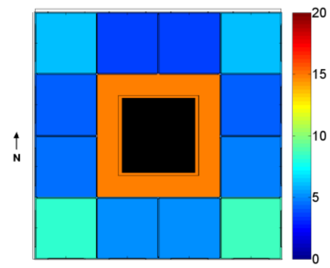
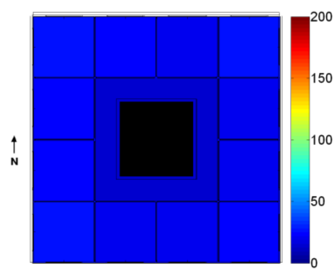
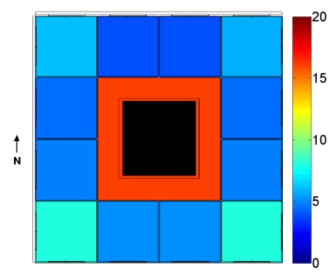
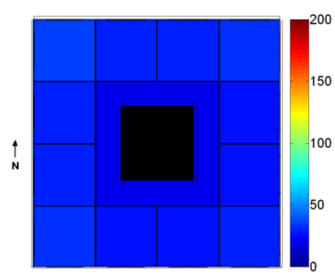
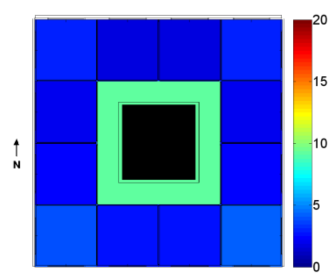
APPENDIX C: COLOR PLOT FOR HEATING AND COOLING DEMAND

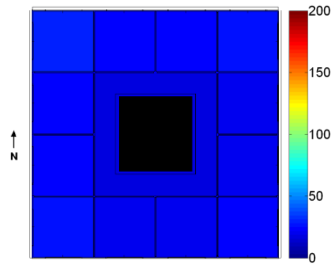
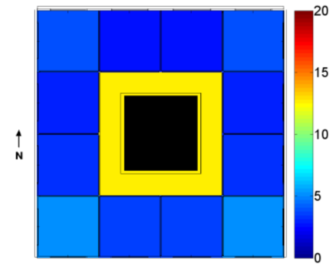
Table C-1 shows the results for cooling and heating demand of the 288 cases in color plots. Each plot represents the plan view of the 12 offices and the corridor of the simulated building's floor.

The nomenclature used is the same explained in Table B-1 (APPENDIX B).

Table C-1. Results in color plots for heating and cooling energy demand by orientation.

A20B1C1	
Cooling, kWh/m^2· year	Heating, kWh/m^2· year
	
A20B1C2	
Cooling, kWh/m^2· year	Heating, kWh/m^2· year
	
A20B1C3	
Cooling, kWh/m^2· year	Heating, kWh/m^2· year
	

A20B1C4	
Cooling, $kWh/m^2 \cdot year$	Heating, $kWh/m^2 \cdot year$
	
A20B2C1	
Cooling, $kWh/m^2 \cdot year$	Heating, $kWh/m^2 \cdot year$
	
A20B2C2	
Cooling, $kWh/m^2 \cdot year$	Heating, $kWh/m^2 \cdot year$
	
A20B2C3	
Cooling, $kWh/m^2 \cdot year$	Heating, $kWh/m^2 \cdot year$
	

A20B2C4	
Cooling, kWh/m^2· year	Heating, kWh/m^2· year
	
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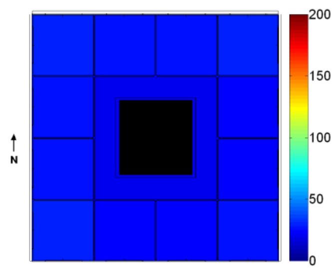
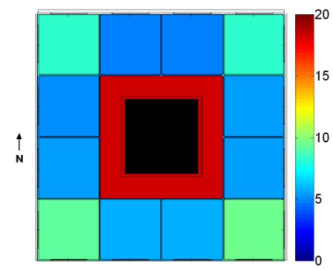
Cooling, kWh/m^2· year	Heating, kWh/m^2· year
	
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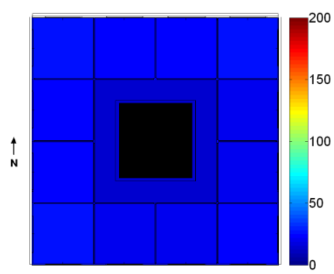	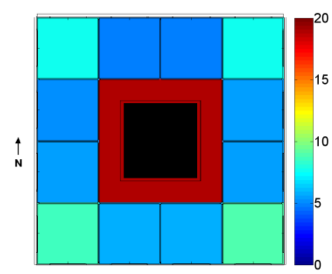
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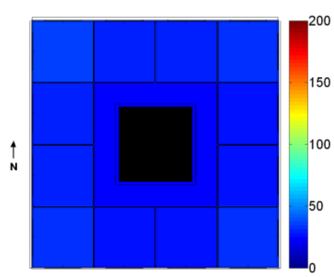	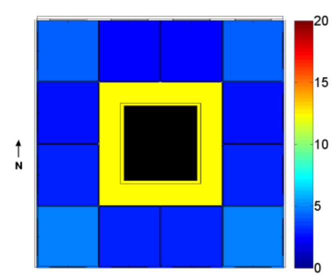

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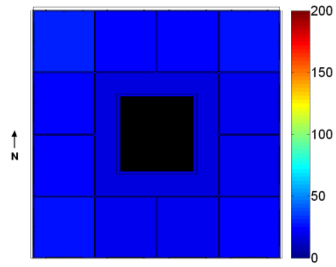	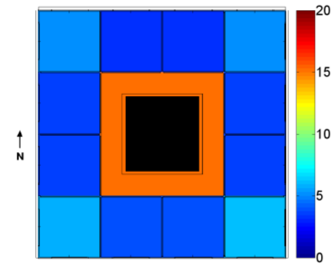
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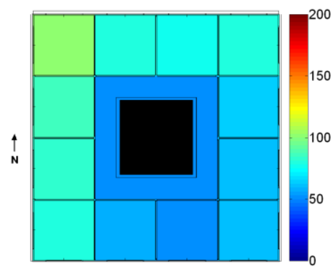	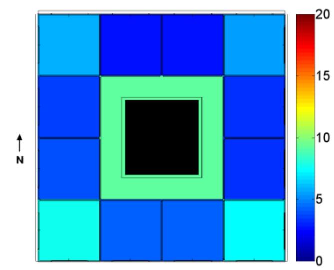
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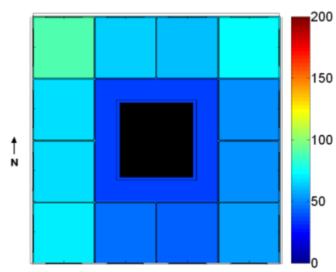	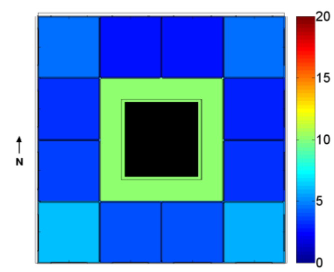
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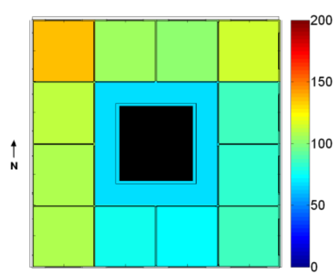	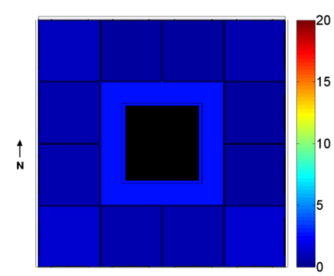

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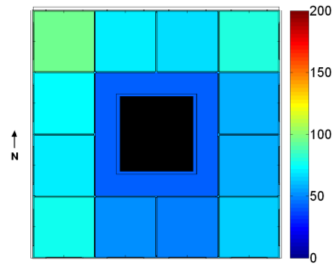	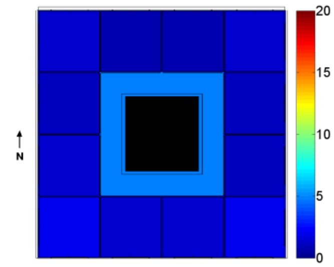
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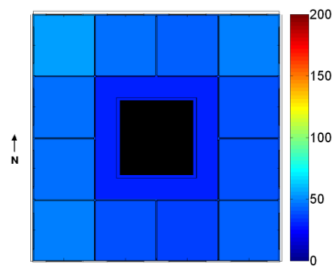	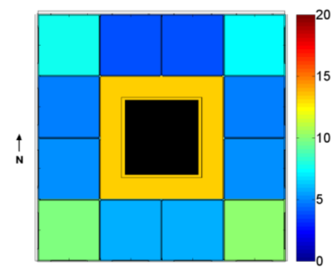
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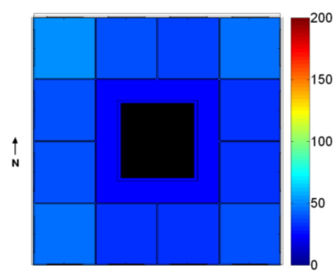	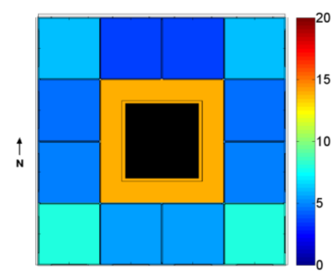
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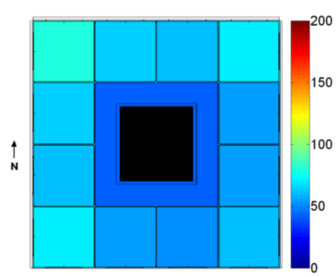	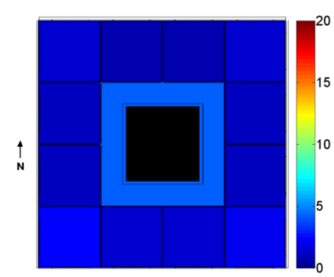

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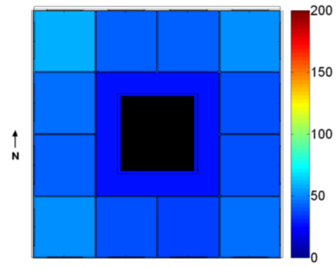	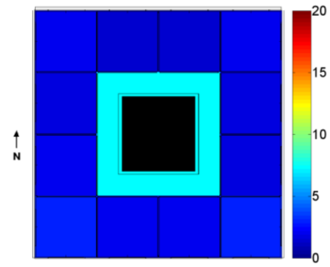

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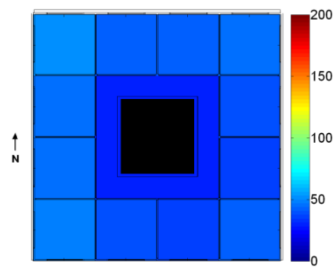	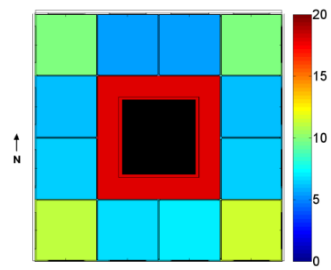

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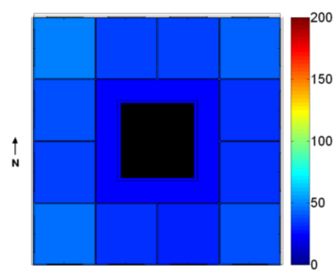	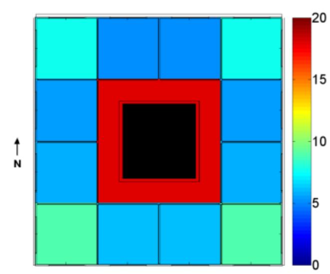

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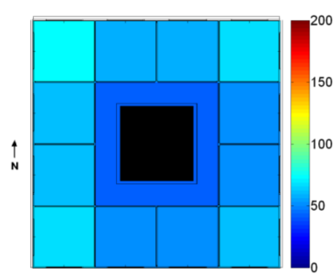	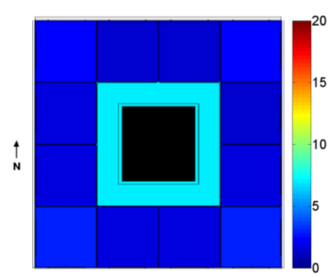

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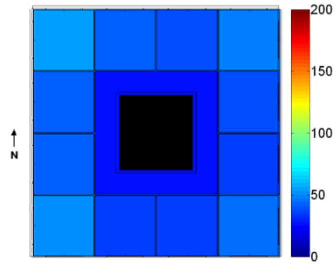
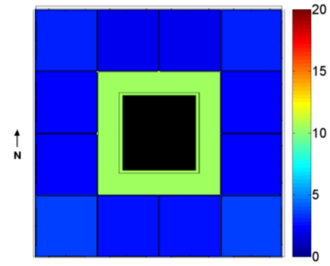
<tr><td>
</td><td>
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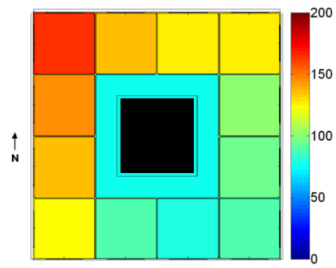
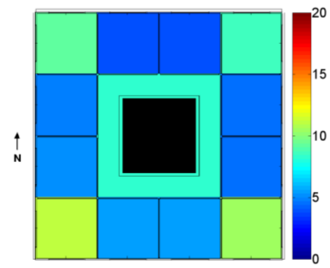
<tr><td>
</td><td>
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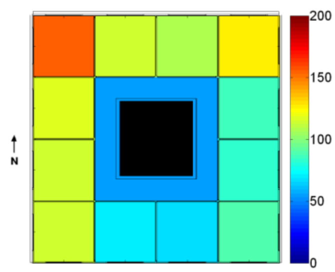
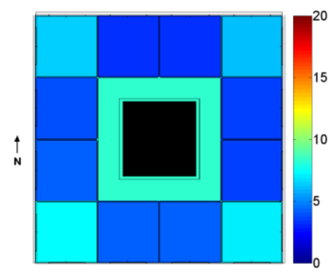
<tr><td>
</td><td>
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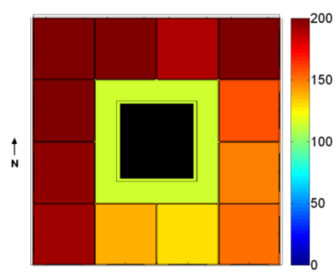
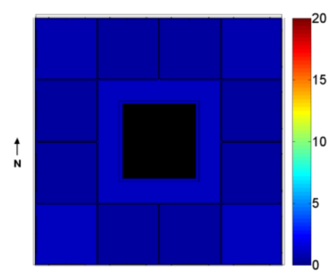
<tr><td>
</td><td>
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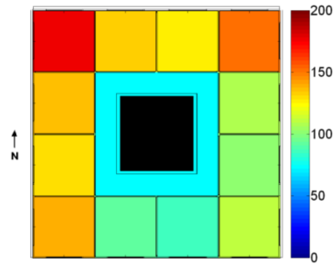
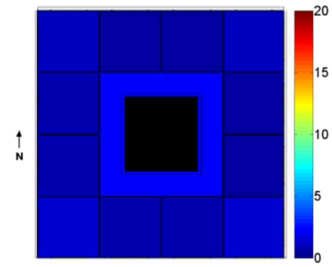
<tr><td></td><td></td></tr>
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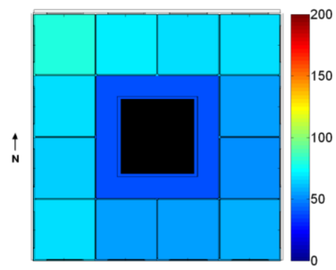
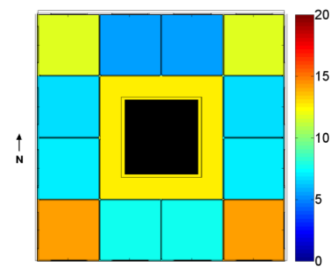
<tr><td></td><td></td></tr>
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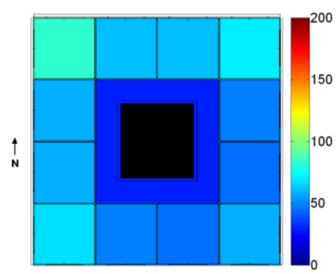
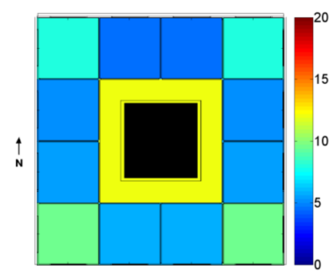
<tr><td></td><td></td></tr>
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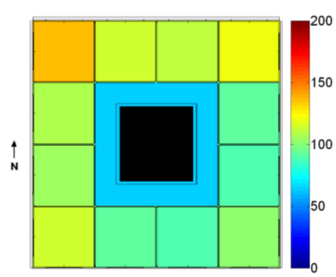
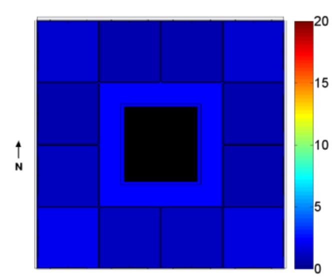
<tr><td></td><td></td></tr>
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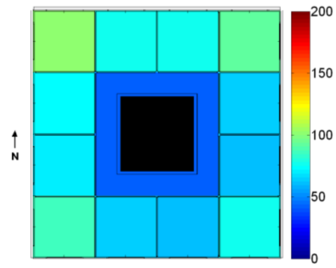	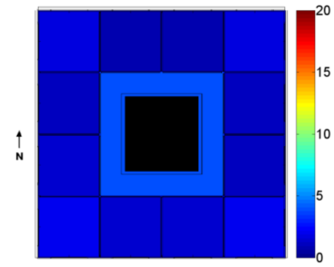

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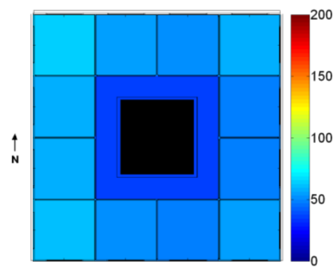	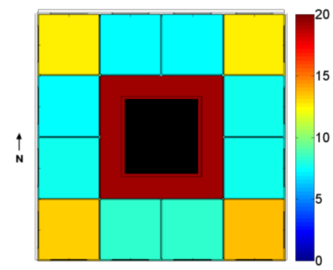

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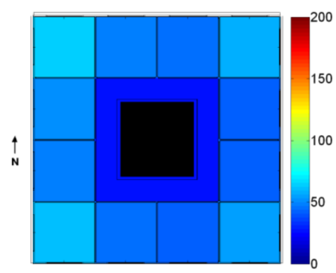	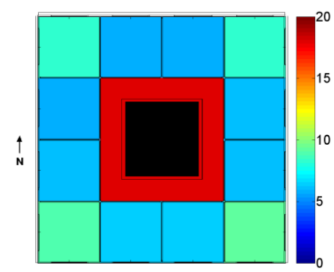

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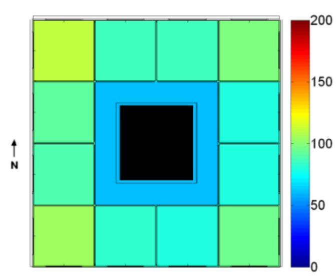	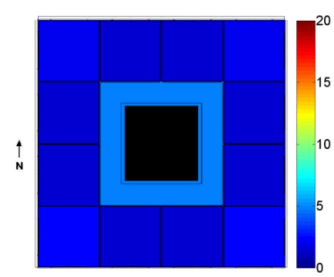

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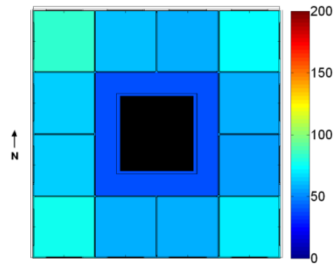	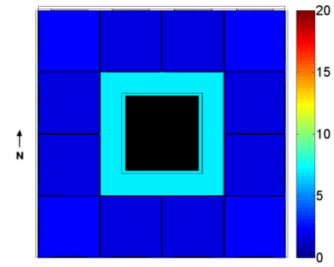

APPENDIX D: CORRELATION BETWEEN HEATING AND COOLING DEMAND AND WWR

Values for heating and cooling demand and the sum of them with their respective WWR for the results of the 36 cases for the complete floor are plotted in the scatterings shown in Figures D-1, D-2 and D-3.

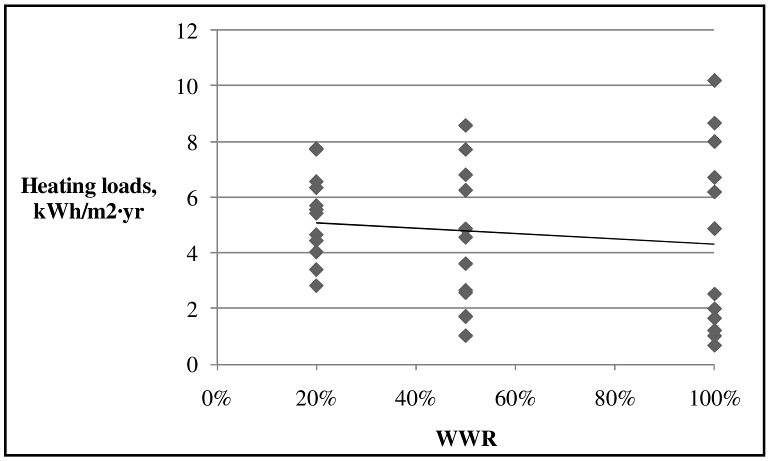

Figure D-1. Scatter plot of heating demand and WWR.

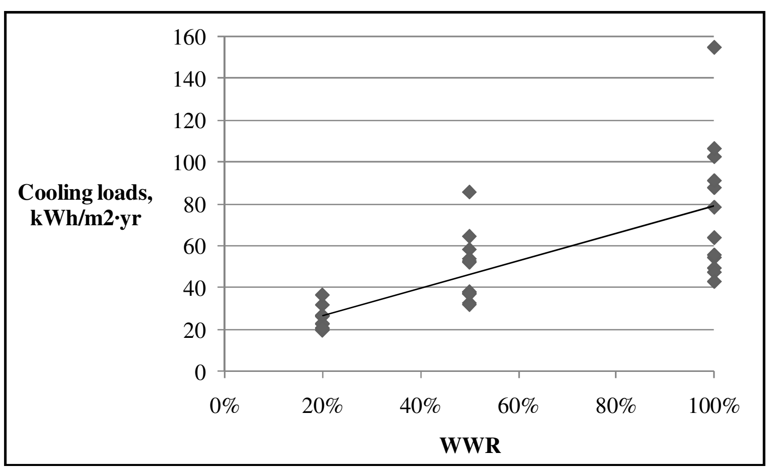

Figure C-2. Scatter plot of cooling demand and WWR.

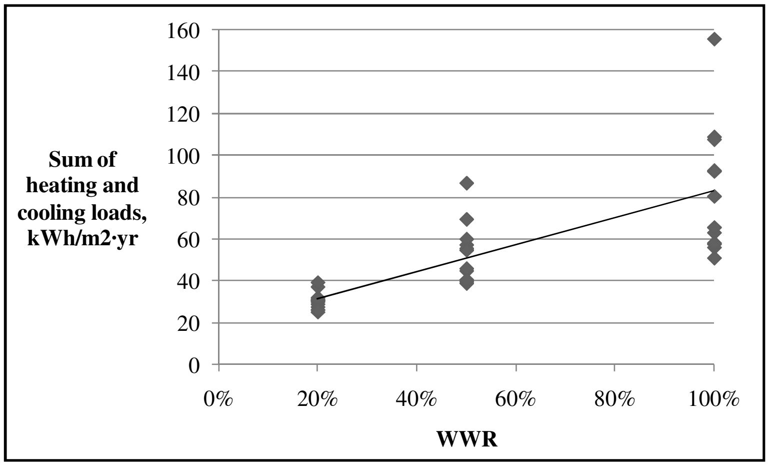

Figure D-3. Scatter plot of total demand and WWR.

Tables D-1, D-2 and D-3 show the correlation coefficients between energy demand and WWR (Pearson's coefficients). This measure indicates a possible linear relationship between two continuous variables measured on the same subject or entity. This coefficient may range from -1 to +1. If the correlation is positive, it means that when one variable increases, the other tends to increase. If the correlation is negative, it means that when one variable increases, the other tends to decrease.

Correlation for heating demand and WWR is negative and weak: -0.127. It means that the value of the WWR does not influence notoriously the value of heating demand. As can be seen in Figure D-1, a higher WWR increases the variability in the results of heating demand.

Correlation for cooling demand and WWR is positive and strong: 0.726. As the cooling demand values are bigger than the heating ones, the total demand (heating + cooling) are also strongly related with WWR.

Table D-1. Pearson's Coefficients for heating demand and WWR.

	HEATING	*WWR*
HEATING	1	
WWR	-0.127	1

Table D-2. Pearson's Coefficients for cooling demand and WWR.

	COOLING	*WWR*
COOLING	1	
WWR	0.726	1

Table D-3. Pearson's Coefficients for the sum of heating and cooling demand and WWR.

	TOTAL	*WWR*
TOTAL	1	
WWR	0.745	1

APPENDIX E: USEFUL DAYLIGHT ILLUMINANCE VALUES

The grid used in the daylight analysis contains 36 nodes. The case analyzed is the configurations that causes the best thermal performance: 20% WWR, N overhang + E&W blinds and selective double glazing. The main statistics measures for the results obtained from Daysim for UDI values when illuminance is useful (between 100 and 2000 lux) and when it is excessive (above 200 lux) for all orientations are shown in Tables E-1 and E-2 respectively.

Table E-1. Statisctics metrics for UDI values (0 – 100 %) when illuminance is useful.

Orientation	Mean	Std. Deviation	Min	Max
N	71.7	21.6	18	88
NE	64.4	22.5	17	85
E	75.6	8.3	64	91
SE	81.6	20.6	25	94
S	85.2	17	30	94
SW	76.2	21.2	22	93
W	82	4.2	75	89
NW	58.5	22.8	15	86

Table E-2. Statisctics metrics for UDI values (0 – 100 %) when illuminance is excessive.

Orientation	Mean	Std. Deviation	Min	Max
N	21.6	22.2	4	76
NE	29.1	23.0	8	77
E	0.0	0.0	0	0
SE	12.1	21.0	0	70
S	8.0	17.5	0	65
SW	17.6	21.6	0	72
W	0.9	3.0	0	12
NW	35.2	23.4	7	80

APPENDIX F: ENERGY DEMANDS RESULTS FROM A SIMILAR RESEARCH

Master's Degree Thesis of Mr. Alejandro Prieto, 2011.

Title: "*Interfaz Ambiental en Edificios de Oficina. Envolvente de Espesor Programático Variable como Sistema de Mediación Ambiental Pasivo"*

Advisor: Claudio Vásquez Zaldivar

Table F-1. Input parameters for building energy simulations.

Simulation Parameters	
Working Time	Monday – Friday, 8 AM – 7 PM
Ventilation + Infiltration	1 ach
Occupation heat gain	Offices: 7.5 W/m^2
	Meeting room: 18.2 W/m^2 (2 hours per day)
	Services: W/m^2
Equipment heat gain	12 W/m^2
Lighting heat gain	20 W/m^2
Comfort temperature	20 – 26 ºC

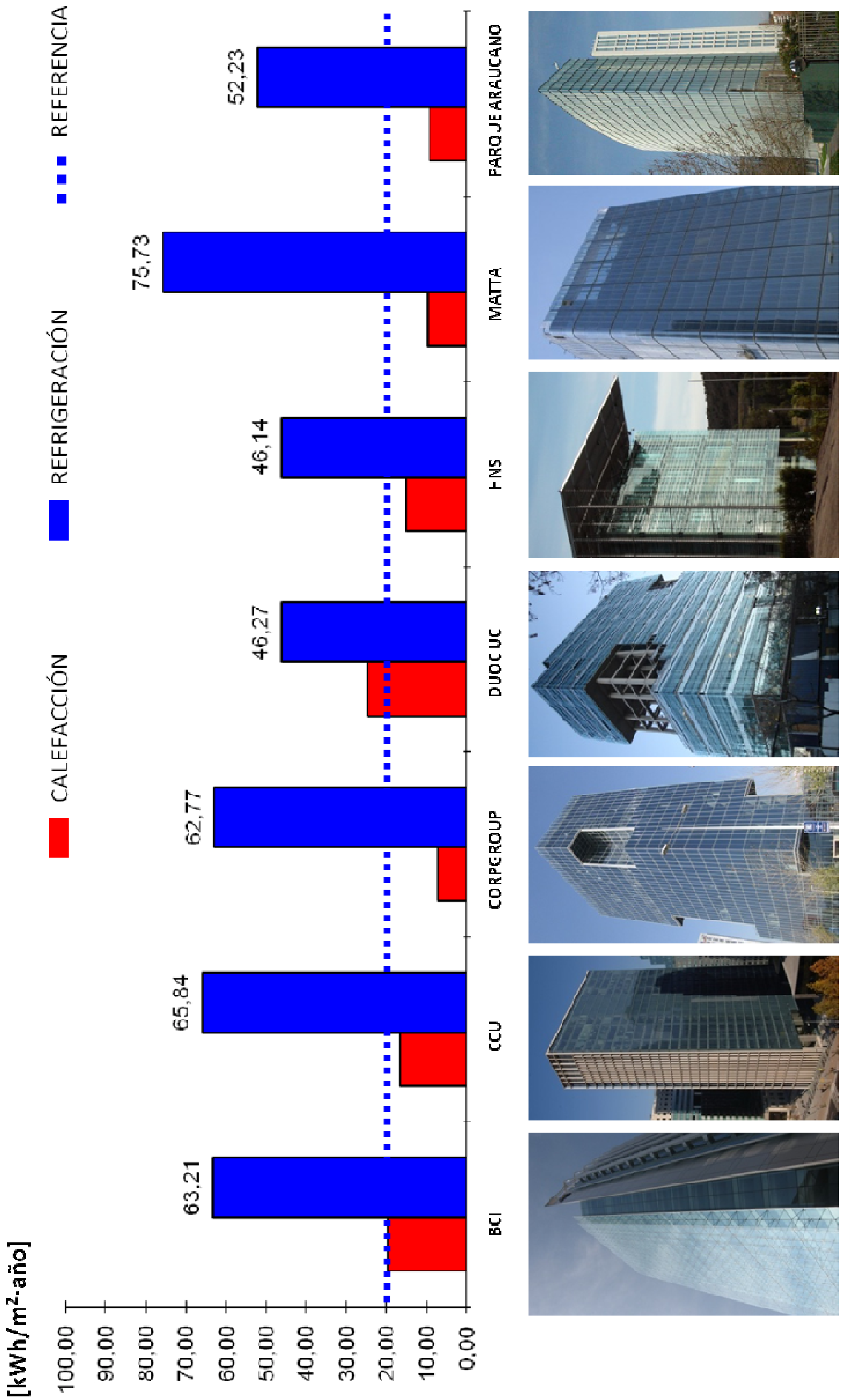

Figure E-1. Energy demand for the 7 buildings studied by Prieto.